International Linear Collider Time Projection Chamber Studies

James Inman
Physics Department, Radford University, Radford, VA, 24142

(Dated: August 11, 2006)

As part of the development of a detector for the International Linear Collider, physicists from Cornell and Purdue are investigating properties of advanced readout devices for a charged particle detection device called a Time Projection Chamber (TPC). Data is collected using a sophisticated multi-channel sampling analog-to-digital-converter data acquisition system. A means has been developed for detecting and comparing the rate of (undesirable) ion feedback, the migration of positive charge back into the detector volume. An analysis package has been created in Microsoft Visual C++.

I. INTRODUCTION

There are currently four detector concepts for the International Linear Collider (ILC), three of which are Time Projection Chambers (TPC) for tracking charged particles. A prototype TPC detector located at Cornell is being used for research and development for future TPC designs to be used at the ILC. The TPC uses an electric field to drift electrons that have been freed from ionization of a neutral gas. The electrons drift to a 2d matrix of readout pads where a signal is collected. Using the drift time for the z-coordinate, tracks can be fully recreated. Ions are produced in the chamber and can migrate back into the detector volume. The positive ions in the gas can then cause interference with tracks. Ion feedback is a component of TPCs that needs to be analyzed, measured, and suppressed. A new method for measuring ion feedback from the gas amplification process has been developed. Positive ions are collected on a plane of wires before they enter the drift chamber by applying a bias voltage. Eight of these wires are monitored and data is collected. To analyze this data, improvements to the analysis package needed to be made. A new analysis program was adapted from the previous fortran version and implemented in Microsoft Visual C++.

II. TIME PROJECTION CHAMBER OVERVIEW

The TPC is a charged particle detection device (Fig. 1). The device consists of a large drift volume, filled with a neutral gas ($ArCO_2$), in which a uniform electric field is maintained (referred to as the field cage). As a charged particle moves through the gas, it collides with gas molecules and ionizes them. The liberated electrons from the ionization are then accelerated towards the end of the of the field cage where they pass through a field cage termination plane of parallel 20 μm wires. The field cage termination is used to maintain a more uniform electric field in the field cage. The electrons then pass through a gas amplifier and a signal is collected on a matrix of metallic sensor pads. Each pad is connected to a preamp and the signal is monitored.

The TPC has a removable endplate which holds the gas amplifier, readout pads, and preamps; the latter of which are connected to the FADC and the VME crate. The FADC is a *flash analog-to-digital* converter which reads in an analog signal from the pads, converts it to 16-bit data which is the placed on a circular buffer. On an event trigger, the data on

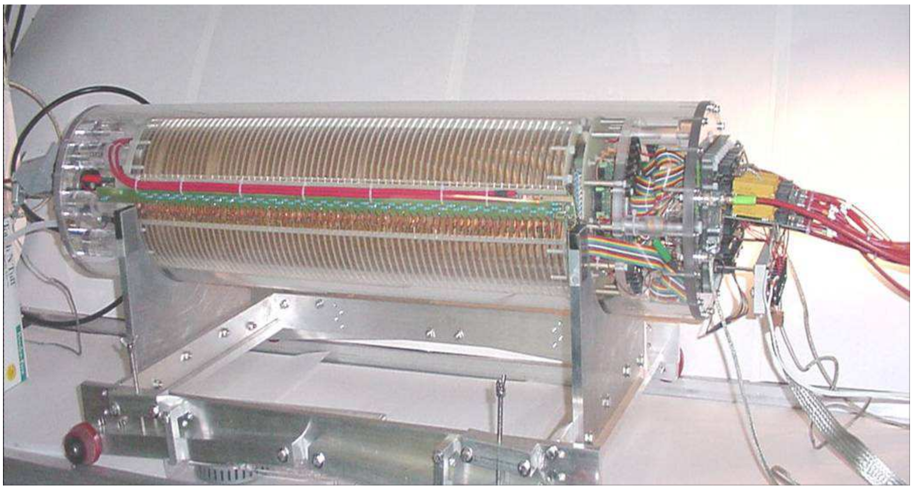

FIG. 1: The Time Projection Chamber.

the buffer is read in by a LabVIEW routine, and is appended to a binary file that has been created specifically for the current run.

The gas amplification turns the relatively small signal into a much larger signal by producing an avalanche of ionization. A wire amplifier (Multi-Wire-Proportional-Chamber Fig. 2) is a plane much like the field cage termination with parallel wires. A large potential difference is placed between the anode (wires of the amplifier) and the the cathode (field cage termination or the pad plane). Naively, one would assume a uniform field between the anode and catode, but this is not the case since the two planes are not uniform equipotential planes. From first principles it is observed that the field near a charged wire decreases with a 1/r dependance:

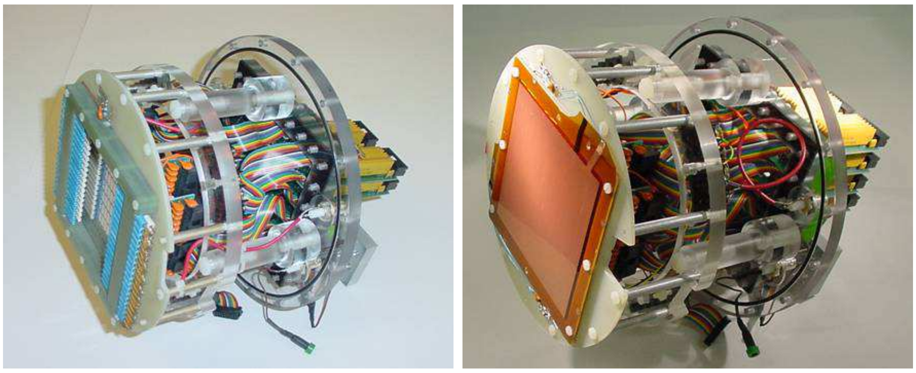

FIG. 2: Multi-Wire-Proportional-Chamber (left) Gas Electron Multiplier (right).

$$E = \frac{\lambda}{4\pi\epsilon_0 r} = \frac{Q}{r} \tag{1}$$

The potential at some distance from the center of the wire is found by integration:

$$V = Q \ln\left(\frac{b}{a}\right) \tag{2}$$

where V is the voltage applied, b is the distance between the field cage termination and the amplifier wire, and a is the wire radius. Solving for Q and putting into equation 1:

$$E = \left(\frac{V}{r}\right) \frac{1}{\ln{(b/a)}} \tag{3}$$

The potential is held at 2100V, the distance $b = 5$mm, and $a = 20$ μm. At the wire surface $r = 20$ μm the field will be $E = 19x10^4$ V/cm. At $r = 76$ μm the field will be $E = 5 \times 10^4$ V/cm. A more thorough analysis may be found in a paper by Sauli, page 40-43 [2]. Inside this radius is where amplification takes place.

The collision length of the electrons with the gas in the chamber becomes important here. Taking the volume per mole of gas to be 22.4×10^3 cm^3 and the approximate cross section of a molecule to be the same order of magnitude as for an atom $(\sim 10^{-8}\text{ cm})^2$ we would find the cross section to be:

$$\left(22.4 \times 10^3\ \frac{\text{cm}^3}{\text{mol}}\right) \times \left(\frac{1\text{ mol}}{6.023 \times 10^{23}\text{ atoms}}\right) \times \frac{1}{(\sim 10^{-8}\text{ cm})^2} = 4\mu\text{m} \tag{4}$$

So the electron should hit a gas molecule about every 4 μm. If the electron is within the amplification area defined by a radius of 76 μm then the field will be greater then 5×10^4 V/cm. This means that the electron will have an energy of at least:

$$\text{Energy} = \text{q} \times \text{V} = \text{e} \times (5 \times 10^4\text{ V/cm}) \times (4\ \mu\text{m}) \approx 20\text{ eV} \tag{5}$$

The average energy to singly ionize an Argon atom is 16 eV [1, 2]. Free electrons inside the ionization radius will acquire enough energy between collisions to ionize the gas producing another electron and so forth in an avalanching pattern until all electrons reach the wire. This process leaves a cloud of positive ions which subsequently induces a signal on the pads. Due to the inductive means of signal transfer from the amplifier to the pads there is a poor resolution. A signal will be induced on several neighboring pads to the pad that is directly in line with the track.

The positive ions then follow the field lines they are on in a direction away from the amplifier wires. A fraction will continue on to the pads and the remainder will drift back into the field cage termination. Because there is greater field on the field cage side, more of the ions go in that direction. This makes the wire amplifier unsuitable, thus two other amplification devices were developed: the Gas Electron Multiplier (GEM) and the Micromegas. Both devices create a region of high field (typically run at 8×10^4 V/cm) to create an avalanche of electrons much in the same way as the wire amplifier. The GEM and Micromegas were designed to minimize ion feedback. Unlike the wire amplifier many of the field lines that create the high field region do not return to the field cage, rather they terminate on the GEM, thus allowing ions to come back to the amplifier and deionize. Quantitative measurements of the ion feedback signal needs to be made to compare the different amplifiers.

III. ANALYSIS PROGRAM DESIGN

Previously, the data was analyzed using a program written in Fortran and run on a Unix system. A new analysis program was designed and written in Microsoft Visual C++. There are several advantages to updating that the analysis program. Written in Visual C++, this program can run on any Windows system. This allows for data analysis in the lab where Windows computers are used. It also eases collaboration with others who run Windows. The primary motivation is the addition of code to allow for the analysis of ion feedback.

The program is typically run using the Windows Form GUI that was developed to interact with the analysis code. The executable is named simpleread.exe. Two data files, channelpadconfiguration.dat and analyzeconfiguration.dat, must be saved in the same directory as simpleread.exe.

The analysis code consists of a single class event.h. The event class contains all variables and methods required for analysis. Data analysis is possible using a short console program that calls member methods of the event class. Usually this is done only for debug purposes and the GUI is used.

After calling the event constructor, which takes no arguments, member methods of the event class are called to load two data files: channel pad configuration and analysis configuration. The channel pad configuration data file contains information about the layout of the TPC such as the number of pad rows and number of pads in each row. It maps the data sets in the binary data file to the (row,pad) coordinates. It also contains the geometry of the padboard. The analysis configuration data file contains 3 sets of 35 input parameters that are used to analyze the data and it includes parameters used in data smoothing, pulse identification, and track fitting.

Member methods of the event class are then called to open a TPC binary data file. A single file can be opened or a data file which contains a list of filenames can be read in to run in batch mode.

Statistical data is output from the program through ROOT objects. ROOT is an object-oriented data analysis framework that was developed at CERN. The TTree class of ROOT is used to create an ntuple tree which will hold data for each event. The TTree object consists of branches that can hold any type of data from integers to classes. The branches are then filled with data for each event that passes the analysis process. The TTree object is then saved to a ROOT file (default.root or specified by the user). The ROOT file can then be opened using stand-alone ROOT (root.exe).

The GUI or console program then loops over events in the TPC data file. The method event::loadmanager() will load the next event in the data file and continue to the next data file if a list of files has been loaded. Then the method event::analyzeevent() is called to analyze the data. Each event consists of 56 buffers of 2048 elements; this data is kept in a 2D array. The analyze method rotates the data buffers (time alignment) and creates a copy of the data that is smoothed. It then searches the data buffers for valid pulses that meet the threshold parameters in the analysis configuration file. If enough pulses are identified the program will attempt to fit a track and calculate the residuals of that fit. The method to get information about the ion feedback signal is called. If the event is identified as a valid track or having a valid ion feedback signal it is saved to a list. The user may save this list to a file and is prompted to do so when closing the GUI. This event list file may be loaded so that the user can 'jump' to events in the list.

When running the GUI, the user may plot the event to the screen. The GUI creates a plot of pulse height vs. time as well as a drawing of the padboard with the fitted track and pads used for fit highlighted. After plotting an event the user may create a bitmap output of the display. The bitmap resolution is set to be 1280x800. The user is prompted where to save the bitmap.

IV. ION FEEDBACK MEASUREMENT

Ion feedback is an undesired effect that is due to the gas amplification in the TPC. The amplification process causes an avalanche of ionization as described above. The positive ions created during this process then drift in the opposite direction of the electrons back into the drift field. If the frequency of events is high (as in a particle accelerator), positive ions can be expected to accumulate in the field cage and begin to effect tracks.

A method for measuring ion feedback; therefore, is required. Normally, at the end of the field cage in the small prototype there is a single field cage termination which is made of parallel 20 μm wires as described in the overview. This plane provides a close to uniform potential plane while still being transparent. It would not collect ion signal; instead, ions would drift past the plane into the field cage just as electrons do. Thus, a double field cage termination is needed. This allows for an area to be defined with a reverse electric field. This reduces transmission of electrons from track and allows for ions drifting back into the field cage to be collected on wires. This is a different method than used by other groups and will allow a more direct comparative measurement of ion feedback in the various devices.

Using a Micromegas amplifier, the transmission effects of the double field cage termination are tested. The bias voltage is varied on the amplifier side of the termination. Data is taken with different field intensities and directions between the two planes of the termination. The pulse height of signals on the pads decrease as the field retards the electron drift as seen in Fig. 3. This data shows that the pulse heights on the pads are reduced to 40% of the full transmission with a change of the bias potential from -306 V to ~(-450 V). An approximate 60% of positive ions should then be collected on the field cage termination.

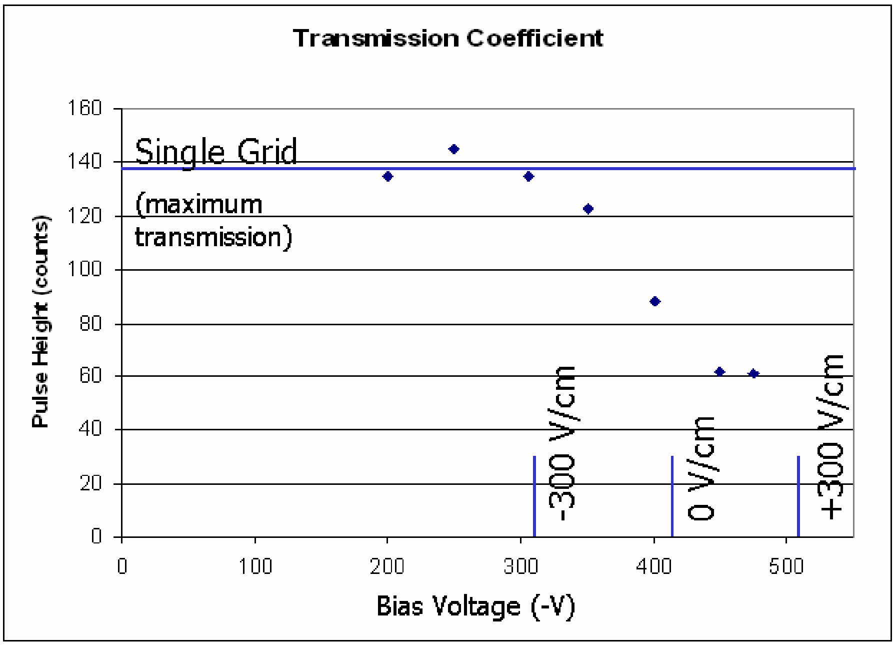

FIG. 3: Pulse height of signal on pads decreases as the field between the two planes of the field cage termination is reversed. Average pulse height of the single field cage termination is shown for reference.

A wire gas amplifier is used as the test amplifier device for initial ion feedback measurements. The wire amplifier produces a large and predictable quantity of ion feedback. With the double field cage termination installed in the TPC, the bias voltage is set to create a 40% transmission mode (see Fig. 4). The traces from the field cage termination show an "fast" inductive pulse as expected from the avalanche of ionization at the amplifier. There is also a pulse observed with a delay time of ≈200 μs after the first pulse. A total of 579 events were looked at for this case and a mean delay time of 202 μs with an RMS of 8.7 μs (Fig. 5). The ratio of the presumed feedback pulse height to the inductive pulse height is recorded with a mean of 6.0% and an RMS of 2.4% (Fig. 6).

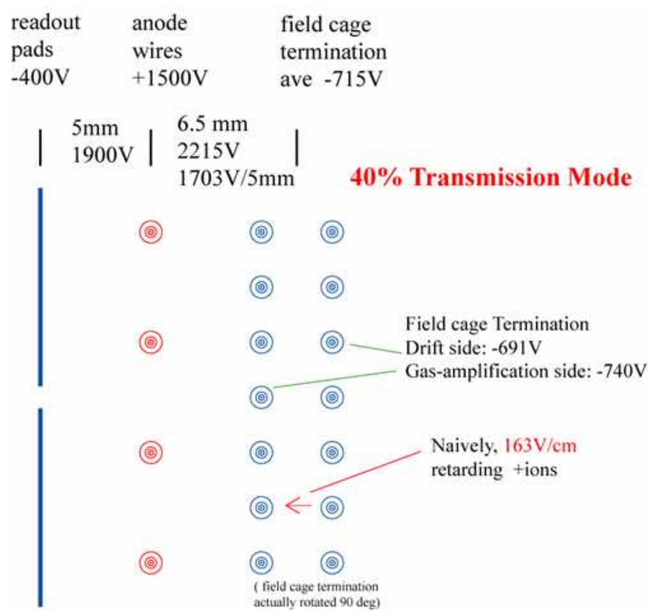

FIG. 4: Schematic showing the bias voltages on the pads (left), wire amplifier (middle), and double field cage termination (right).

The bias voltage on the field cage termination is then set to values which naively should provide full transmission. There is still a delayed pulse signal on the field cage termination trace; however, its pulse height has decreased and the delay time remains constant. The bias voltage now set to provide a potential difference which is more than necessary for full transmission, acceleration of the ions through the field cage termination. The pulse height of the feedback is further reduced. The decreased signal to noise ratio makes pattern-recognition difficult for this run. The delay time remained constant. See TABLE I for data.

The drift distance between the amplifier and the field cage termination can be changed. In order to eliminate the possibility of the observed signal being cause by and electronic source the drift distance was increase from 5mm to 7mm. Bias voltages were set to recreate the 40% transmission mode. Again a delayed pulse was seen on the field cage termination. The delay time was noticeably longer. The run produced 91 events, with a mean delay time was 245 μs and an RMS of 7.9 μs. This is a 21% increase in delay time while the drift distance was increased by 40%. The pulse height ratio was comparable to the 5mm run. The mean pulse height ratio was 7.4% with an RMS of 2.8%.

The wires of the field cage termination are aligned parallel to the y-axis of the padboard. The center eight wires of the field cage termination are monitored individually. Although

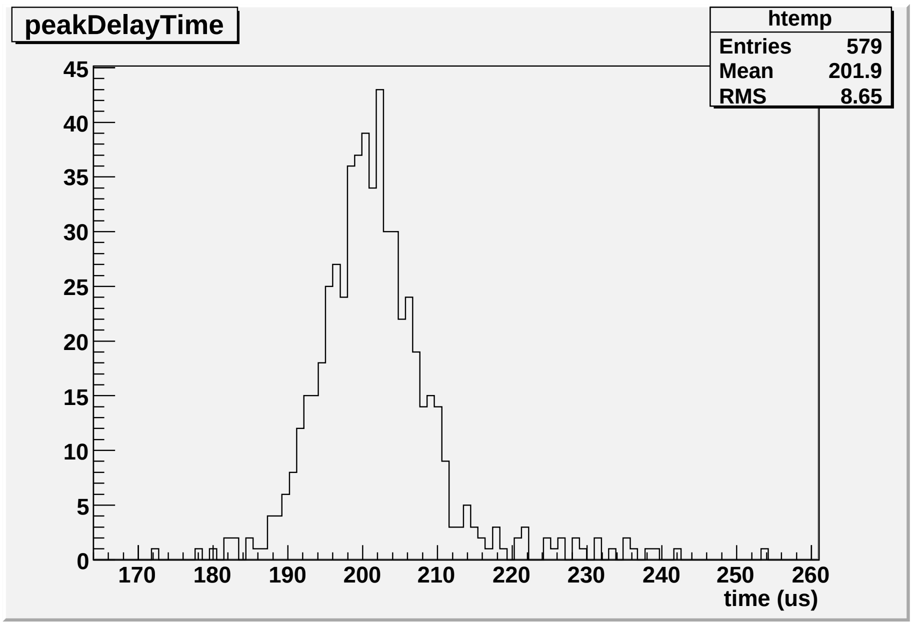

FIG. 5: Histogram of the difference between the inductive pulse time and the feedback time measured from peak to peak of the pulses.

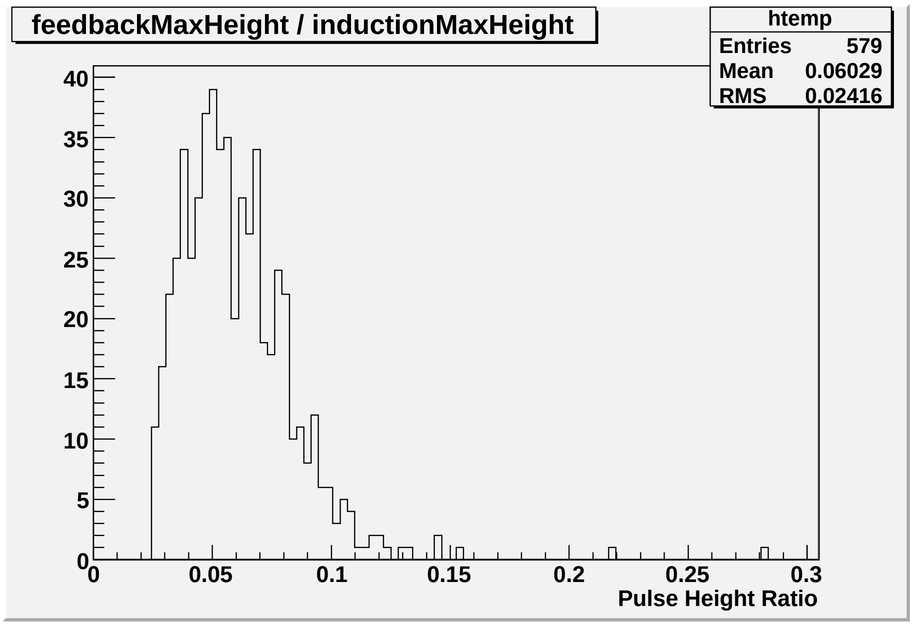

FIG. 6: Histogram of the ratio of inductive pulse height to the feedback pulse height (using smoothed data).

the inductive signal is seen on several of the wires, the ion feedback signal is collected on a single field cage termination wire. The ion feedback signal is observed to correspond well with the x location of the track. This further supports that the signal corresponds to ions drifting from the amplification location.

TABLE I: Ion feedback summary. RMS values given in parenthesis. Drift Side and Gas-Amp Side are the field cage termination bias potentials

Transmission	Drift Distance (mm)	Drift Side (V)	Gas-Amp Side (V)	Drift Time (μs)	Relative Pulse Height (%)
40%	5	-691	-740	202 (8.7)	6.0 (2.4)
“Full”	5	-730	-640	207 (9.3)	4.2 (2.0)
“>Full”	5	-730	-540	216 (21.)	2.6 (2.0)
40%	7	-988	-937	245 (7.9)	7.4 (2.8)

V. CONCLUSIONS

A new display and analysis program in Microsoft C++ that can be used to analyze ion feedback was developed. The program includes an event class which is used to load, store, and analyze data as well as a GUI that is used to call the event class and produce graphical output of the data.

Using a double field cage termination, ion feedback was measured for a wire gas amplifier which has a large gain. This new technique is a direct measurement of the ion feedback. An attempt was made to measure ion feedback from a double layer GEM amplifier; however, the GEM has an expected gain that is 10% of the wire amplifier and produces only 5% of the ion feedback. Additionally, event recognition is complicated because the GEM amplifier will not produce an inductive signal on the field cage termination, which provides a reference signal to the ion feedback. In this case, a positive ion feedback signal could not be identified above the background electronic noise.

An improvement to the current set up would be to make a pulsing voltage bias on the field cage termination to allow full transmission of electrons and then pulse field to collect ions. A pulsing circuit for this purpose is in design. The TPC will also need new electronic preamplifiers that can withstand pulsing bias voltage. Replacing the wires on the field cage termination with smaller diameter wires (20 μm - 8 μm diameter) would increase the field near the wire, increasing feedback signal. A triple layer GEM would provide much more pad signal amplification.

More measurements of ion feedback need to be made, specifically with regards to measuring ion feedback for various amplifier devices.

VI. ACKNOWLEDGMENTS

I would like to thank Dan Peterson of Cornell University for being my mentor and guiding me through my research experience. Thanks to Tarek Anous for his encouragement and programming assistance. Thanks to Chris Macklin for getting me started with ROOT and to LEPP Computing. Thanks to all the other REU students for adding plenty of excitement and support. And much thanks to Rich Galik for his dedication to the REU program and genuine interest in the success of all the REU students. This work was supported by the National Science Foundation REU grant PHY-0353994 and research co-operative agreement

PHY-0202078.

[1] Blum and Rolandi. “Particle Detection with Drift Chambers”. p.6 (1994).

[2] Sauli, F. *Principle of operation of multiwire proportional and drift chambers* CERN 77-09. (1977).