Straw Characterization based upon ^{55}Fe plateau

Miguel A. Morales
University of Puerto Rico, Mayaguez Campus,
PO Box 9025 Mayagüez PR 00681-9025

Supervisor: Alan Hahn
Fermi National Accelerator Laboratory
PO Box 500 Batavia, IL 60510-0500

SIST Summer Program - Fermilab

Abstract:

A careful analysis of the lower edge of the plateau allowed us to study and understand different aspects of the operation of the straw detector. As a result of the series of measurements made, several parameters were found with which we could perform quality control tests on the detector. To measure and compare the quality and uniformity of the straws in the module, the height of the plateau was found to be a good parameter, because it is easy to measure and produces reasonable results. Because the height of the plateau depends on the straw position when photons are used to ionize the gas, the voltage at the edge of the plateau is a better parameter to study the gain variations. For the prototype detector studied, the edge voltages were found to lie between 1090 and 1110 volts, which correspond to gas gains between 1800 and 2200. From the data collected, additional calculations were performed. Gain variations across the straws were used to discriminate between normal and leaky straws and the slope of the edge of the plateau was used to get an estimate of the equivalent noise in fC in the electronics. A value of 0.49 fC was found for the noise level and leaks in 4 straws were identified.

I. Introduction

The successful operation of a particle detector depends on the quality and uniformity of its parts. For a Straw Detector, in order to achieve the desired tracking resolution, parameters such as wire and straw tension, gas concentration and purity, gas pressure, etc. must be precisely controlled. Before the assembly of the detector, rigorous tests must be done on all the different parts of the detector to assure that they have the desired quality. At this point, precise and direct tests are done. Once the detector is assembled, direct measurements of some of its components are no longer achievable, so we must rely on indirect methods. Throughout this paper, a study of the lower edge of the plateau curve of a Straw Prototype Detector is presented. The main purpose of this study is to find suitable parameters to be use as part of the quality control tests during the detector assembly.

The Straw Prototype Detector under study was built as part of the development of the Straw Chamber Detector for the BTev project, an experiment whose long term goal is to carry out precision studies of CP violation, mixing, and rare decays of b and c quarks in the forward direction at the Fermilab Tevatron collider [4]. The Straw Chamber Detector is part of the forward tracking system, whose major functions are to provide momentum measurements for tracks found in the pixel system, to reconstruct and measure all parameters for tracks which do not pass through the vertex detector, and to project tracks into the RICH counters, EM calorimeters, and Muon detectors [3].

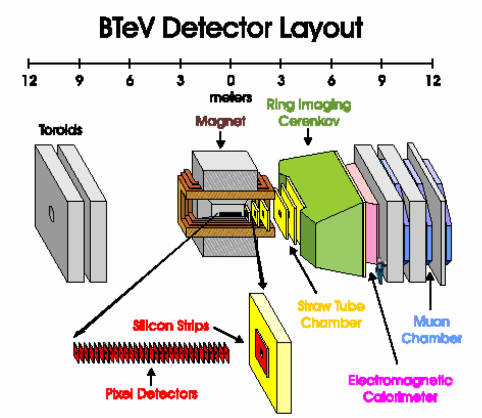

Fig. 1 BTev Detector Layout

To study the characteristics of the straw detector, a study of the lower edge of the plateau curve was done with a ^{55}Fe ionization source. This method provides a good approach because of the strong dependence of the plateau curve with gain variations within the straw. To obtain more precise and uniform calculations, a parameterization of the lower edge was performed using a cumulative distribution function. This parameterization provided enough parameters to fully study the characteristics of the desired part of the plateau curve. Measurements were taken with the source at different positions and with different gas rates and flow directions (flowing from the electronics end\ flowing toward the electronics end). From these measurements, several parameters, with their appropriate ranges, were found with which we could measure the straws' uniformity within a module. Also, noise levels in the electronics were estimated and irregular behavior in some straws lead to the discovery of gas leaks.

II. Background Material

A. Photon Detection

There are three fundamental processes responsible for photon detection in a straw detector: photoelectric effect, Compton scattering, and pair production. From the three, only the photoelectric effect significantly contributes to the photon detection at the energies studied (5.89 keV), having a cross section for absorption almost two orders of magnitude higher than the Compton Effect. Pair production does not occur at this energy.

The photoelectric effect is a process by which one of the electrons in the electronic shell absorbs a photon and gains enough energy to escape from the atom. The energy of the emitted electron is: $E_? - E_k$, where $E_?$ is the energy of the incoming photon and E_k is the energy of the shell where the electron was originally located. Photoelectric absorption in a shell with energy $E_ß$ is only possible for photon energies: $E_? = E_ß$. After the emission of the electron takes place, the atom can return to its ground state by two competing mechanisms of de-excitation [1]:

- fluorescence: the transition of an electron from a higher energy shell into the, now empty, shell with the emission of a photon of energy equal to the difference in energy of the two shell.
- radiationless transition: internal rearrangement of the electronic shell involving the emission of an electron of energy close to the energy of the empty shell. This is also known as the Auger effect.

For Argon, the probability of de-excitation by photon emission, after photoelectric absorption, is around 15% [1]. The secondary photon emitted by the atom has an absorption length of approximately 4cm, and as a consequence, it can escape from the detector's volume carrying energy with it. This is known as an escape peak.

If the energy of the incoming photon is high enough, the emitted electron has enough energy to produce additional ionizing collisions in the gas volume. The total number of ion pairs produced by the absorption of a photon in the gas can be conveniently expressed as [1]:

$$(1) \qquad N_{Total} = \frac{\Delta E}{W_i}$$

, where ?E is the energy deposited in the gas volume and W_i is the effective average energy needed to produce an ion pair.

B. Avalanche Multiplication

Avalanche multiplication occurs when the drifting electrons in the gas gain enough energy, from the electric field, to produce ionizing collisions with the atoms. In cylindrical gas chambers, this phenomenon normally occurs very close to the anode wire where the electric field is very intense. This is the basis of operation of the straw detector. The primary electrons (electrons produced by the incoming particle/photon) can not produce a signal high enough to be detected by the electronics, so the number of electrons must be increased enough to produce a detectable signal, but still being proportional to the number of primary electrons. The gas gain is defined as the total number of electrons that reach the anode wire divided by the number of primary electrons. As can be expected, the gain is strongly dependant on the voltage in the chamber. Normal values for gas gain in proportional detectors are between $10^3 - 10^5$.

C. Time evolution of the electronic signal

Avalanche multiplication is a process that occurs very close to the anode wire, typically at distances less than 50 µm from the wire [1]. Because of this, the distance traveled by most of the drifting electrons is very small, making almost no contribution to the electronic signal (less than 1% of the total charge [1]). Nearly all of the entire signal comes from ions drifting slowly to the cathode. Figure 2 shows an example of the time development of the signal (charged collected by the electronics). As can be seen from the figure, at the beginning the growth of the signal is very fast. This characteristic of the signal creates the possibility of using only the charge collected by the wire in a few nanoseconds, typically 10-20% of the total charge, to detect a hit. This is useful because usually the detectors are used in environments with high hit rates, and using just the first part of the signal reduces considerably the dead time of the detector.

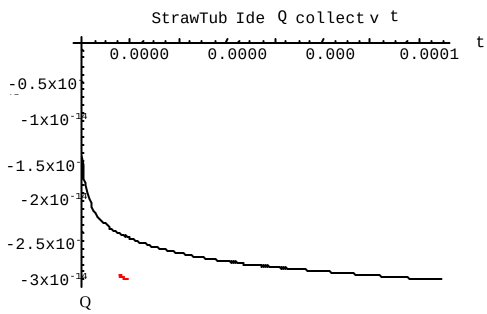

Fig. 2: Time Development of the signal

III. Experimental Setup

The Straw Prototype Detector consists of 2 modules containing 48 straws each of which has a diameter of 4mm and are closely packed in 3 planes of 16 straws. They are made of two 25 µm layers of Kapton films. The inner one, which is next to the gas volume, is carbon loaded. Between the Kapton layers, there is a thin (0.2 µm) aluminum layer that works as the cathode. The wire has a diameter of 25 µm, and it is made of gold(Au)-coated tungsten (W). The straws are 1 meter long. The gas in the straws was Ar/CO_2 in an 80/20 mixture. This gas has a low drift velocity and good ageing properties. Only one of the modules (48 out of 96 straws) was studied.

To study the plateau curve, we used an ^{55}Fe ionization source. The ^{55}Fe source produces x-rays with energies K_a = 5.89 keV and $K_ß$ = 6.49 keV. The source was placed at different positions in the module to study the behavior of the straws. These positions were approximately 16.5cm, 35.5 cm, 52 cm, 66 cm, and 90 cm; all taken from the electronics' end of the module. All the measurements where taken with the source at a vertical distance of 25.5 cm from the middle straw layer. Figure 3 shows a diagram of the experimental setup. Two different gas flow rates were used: 0.4 scfh (standard cubic feet per hour) and 0.9 scfh. Measurements were taken with the gas flowing from the electronics end and towards the electronics end of the module. This was necessary in order to look for leaky straws.

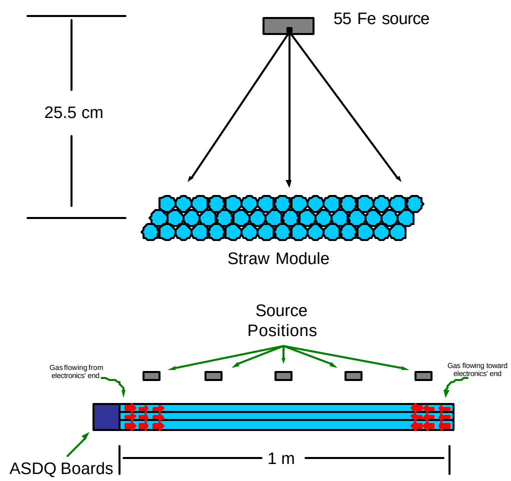

Fig. 3: Experimental Setup

IV. Theory and Results

A Cumulative Distribution Function (CDF) is defined as the integral of a normalized Gaussian distribution. It perfectly resembles the shape of the lower plateau edge and accurately provides the mid point and the height of the curve, which are used to study the straws. Figure 4 shows an example of a CDF fitted to a measured plateau curve. The actual fit is a linear combination of CDFs, because the escape peak of Argon produces a second plateau.

$$\Theta(x) = \frac{1}{\sqrt{2ps}} e^{-\frac{1}{2}\left(\frac{x-m}{s}\right)^2}$$

$$CDF(m, s) = \int_{-\infty}^{x} \Theta(x)dx$$

$$Fit = a * CDF1 + b * CDF2$$

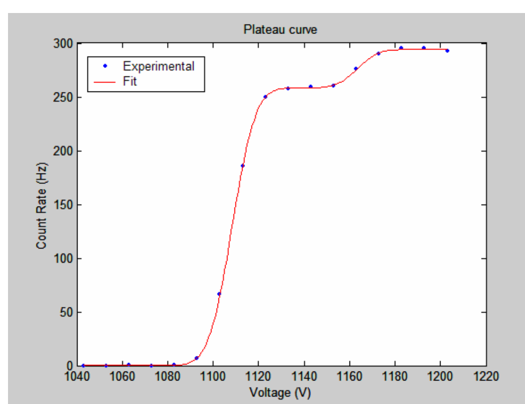

Fig. 4: Example of measured and fitted plateau curve.
Fit parameters: a = 258.3369, ß = 35.7633,
µ1 = 1108.3, s1 = 8.0276, µ2 = 1163.6, s2 = 7.1562.

The ^{55}Fe source emits, as mentioned before, characteristic x-rays with energies: K_{a1} = 5.8990 keV, K_{a2} = 5.8876 keV and K_{β} = 6.4904 keV; the first two can't be resolved. Argon has characteristic x-ray energies: K_{a2} = 2.9577 keV and K_{a1} = 2.9556 keV, which can't be resolved either. This produces an escape peak with energy 2.69 keV. Figure 5 shows the ratio between the gain at the second edge and the gain at the first edge of the plateau as a function of the straw electronic channel number; the gas is flowing from the electronics end at 0.4 scfh, and the source is located at a distance of 20.5'' from the same end.

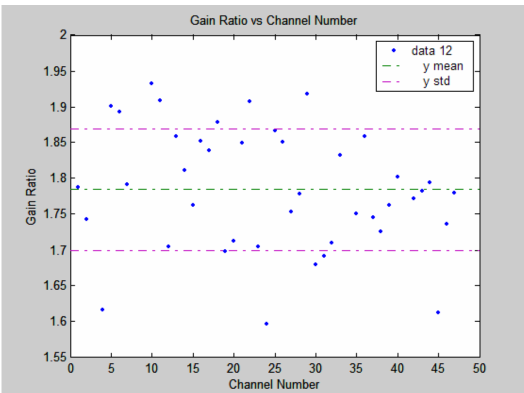

Fig. 5: RMS Gain Ratio = 1.79

The total number of electrons that reach the wire is:

*N = # primary electrons * gas gain.*

If we assume that in order to reach the threshold of the system a specific number of electrons is needed, we can calculate the value of the gain ratio using the energy deposited by the photons in the gas volume:

$$\frac{\text{Gain at 2 edge}}{\text{Gain at 1 edge}} = \frac{\text{PE}(5.89)}{\text{PE}(3.2)} = 1.84$$

, where PE(x) is the number of primary electrons produced by an x-ray of energy x. The rms gain ratio measured is 1.79, which has an error percent of 2.72% with the expected value.

A. Uniformity of the beam distribution

The position and the distance of the source above the straws were selected so that the beam distribution across the straws was uniform. This was a necessary condition if we were to compare measurements between straws.

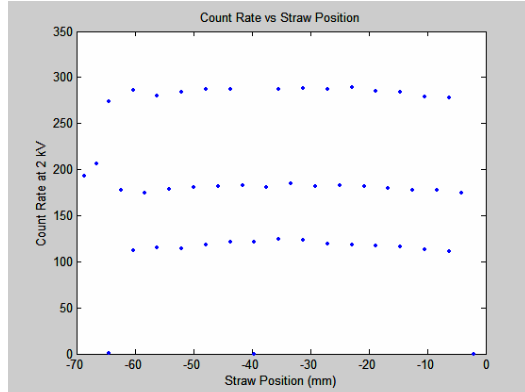

Fig. 6: Count Rate vs Straw Position at 2 kV.

Figure 6 shows the straw count rate in Hz at 2 kV as a function of position. As is shown, the beam is uniform across the straw layers in the module, but is not uniform between layers. This is a direct consequence of the shielding caused by the upper layers in the module. The beam attenuates as it goes through the straw material and a smaller fraction of photons arrives at the lower layer. The two leftmost straws suffer less shielding because there are no straws above them as a consequence of the module geometry, explained earlier. Because the height of the plateau (magnitude of the count rate) strongly depends on the straw position in reference to the ionizing source, it is not the most appropriate parameter to study gain variations. Still, it is a useful tool to measure the uniformity and efficiency of the straws in the module.

B. Edge Voltage

We defined the edge voltage to be the voltage at the mid height of the edge, which corresponds to the mean of the CDF. It is a better parameter to study gain variations across the straw because it is closely related to the threshold in the system and the gain in the straw. This relation comes from the fact that the edge of the plateau is the point where the signal amplitude, which is proportional to the gas gain, reaches the threshold of the system. By simply having a constant threshold in all the measurements, the edge voltage gives us a way to directly compare the effective gain in the straws under different conditions. Figure 7 shows the edge voltage as a function of straw position and Figure 8 shows the gain. The edge voltage does not seem to depend on the straw position within the module, making it a good parameter to measure the efficiency of the straws.

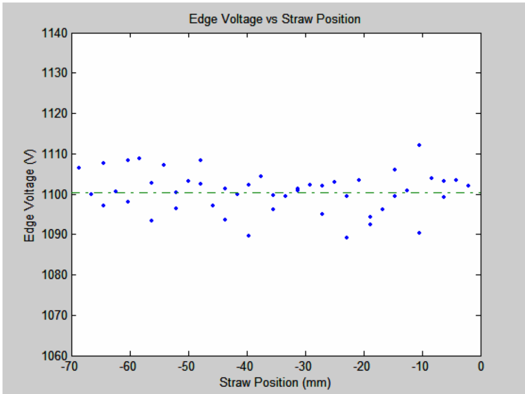

Fig. 7: Edge Voltage vs Straw Position. Gas flowing from the electronics end at 0.4 scfh, the source is located a distance of 6.5''.

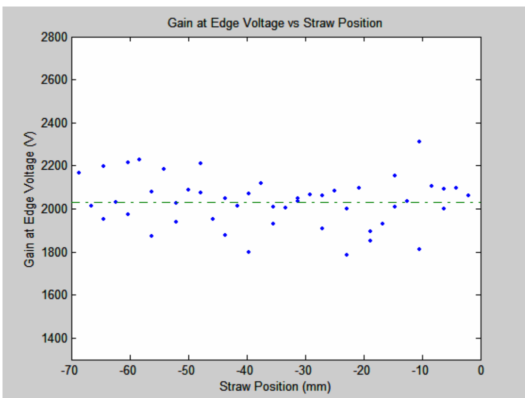

Fig. 8: Gain at edge voltage vs Straw Position. Gas flowing from the electronics end at 0.4 scfh, the source is located a distance of 6.5''.

Another interesting feature of the edge voltage is its dependence with the source position along the length of the straws. When the electronic signal is developed at the anode wire, it splits into two oppositely moving parts, one traveling toward the electronics and the other traveling in the opposite direction. The signal traveling to the end opposite to the electronics bounces off and travels back. Because each signal must travel different distances to reach the electronics, they will arrive at different times and the measured signal (total amount of signal reaching the electronics) will be different. Because we are only measuring the count rate of the straws and not the amount of charge collected at the anode, this effect can not be seen at high gains where the signals produced are several times bigger than the threshold. But at low gains, where the difference between the signals produced and the threshold is very small, the effect becomes an important one.

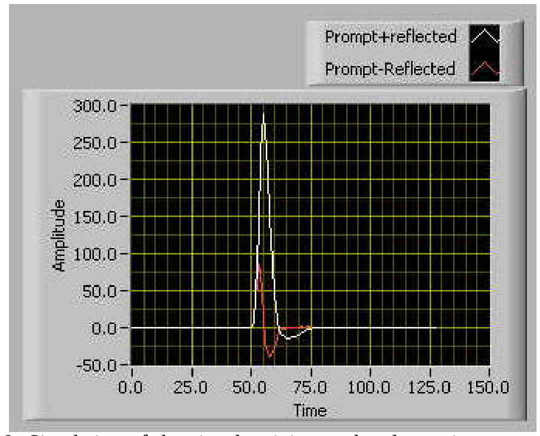

Fig. 9: Simulation of the signal arriving at the electronics. The source is located at the end opposite to the electronics'.

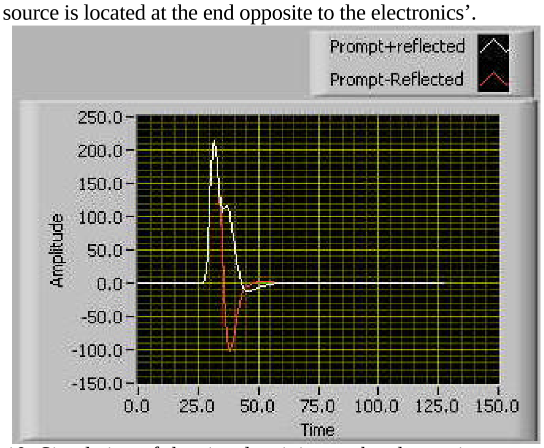

Fig. 10: Simulation of the signal arriving at the electronics. The source is located at the near the electronics' end.

As can be seen from figures 9 and 10, the signal produced in the end opposite to the electronics is higher because the difference in distance traveled by the signals is small. The peaks of the signal arrive at the electronics almost at the same time, producing a higher overall signal. As the source moves toward the electronics, this difference increases and the amplitude of the measured signal is lower. The effect of the attenuation can also be seen.

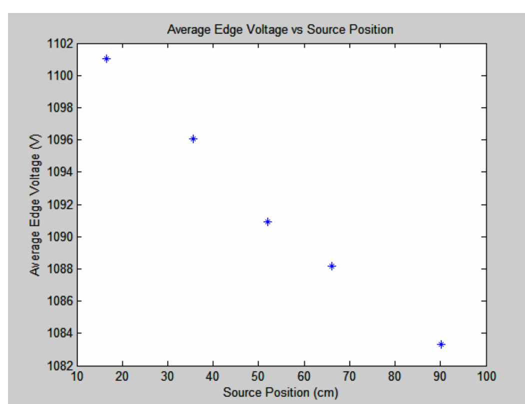

Fig. 11: Average Edge Voltage vs Source Position (measured from the electronics end of the module).

Figure 11 shows the decrease in the edge voltage as the source is moved away from the electronics. Even though the effect can be clearly seen, no definite conclusions were made. A more rigorous study is needed to fully comprehend the phenomena and produce a consistent model.

C. Gas Leaks

From the discussion developed in the last section, we know that the edge voltage is expected to change as the position of the source changes in the module. This variation of the edge voltage is a consequence of the design of the detector and the electronics. In principle, it should not depend on the direction of the gas flow or on the flow rate. Taking this into consideration, it is possible to look for gas leaks in the straws. Assuming that a gas leak would produce contamination downstream of the leak, and that the contamination reduces the gain in the straws, the following parameter was developed to detect gas leaks:

$$d = \frac{\left(EV(90) / EV(16.5) \right)_T}{\left(EV(90) / EV(16.5) \right)_F} \quad (2)$$

where EV(x) is the edge voltage of the plateau with the source at location x (in cm from the electronics), T means that the measurements are taken with the gas flowing toward the electronics and F means with the gas flowing from the electronics.

If there are no leaks in the straws, we expect d=1 because the edge voltage does not depend on the direction of flow of the gas. On the other hand, if there are leaks located near the center of the straw, the edge voltage measured near the end opposite to where the gas is flowing in is going to be higher than normal as a consequence of the leaks. Thus, when the gas flows toward the electronics:

$$\left(\frac{EV(90)}{EV(16.5)} \right)_{with-leaks} \le \left(\frac{EV(90)}{EV(16.5)} \right)_{without-leaks}$$

, and when the gas is flowing from the electronics:

$$\left(\frac{EV(90)}{EV(16.5)} \right)_{with-leaks} \ge \left(\frac{EV(90)}{EV(16.5)} \right)_{without-leaks}$$

, so in general we expect d<1 for leaky straws. Figure 12 and 13 show the leak parameter calculated for the straws with the gas flow rate at 0.4 scfh and at 0.9 scfh respectively.

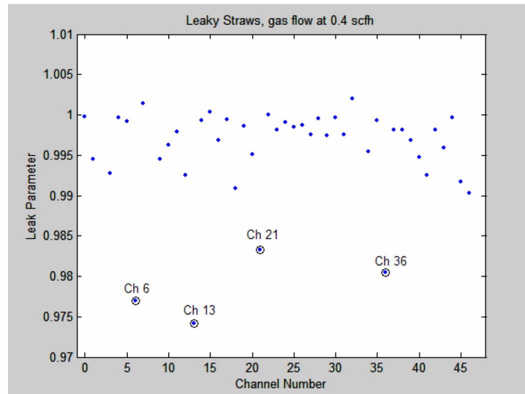

Fig. 12: Leak parameter d as a function of straw channel number. The gas flow is at 0.4 scfh.

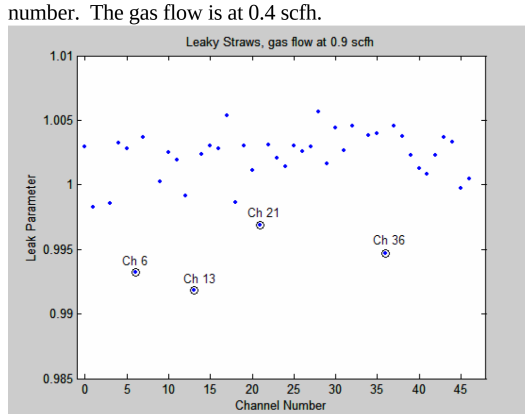

Fig. 13: Leak parameter d as a function of straw channel number. The gas flow is at 0.9 scfh.

As can be seen from the figures, the leaky straws are consistent in both measurements. Even though this is not a precise measurement of the gas leak, this gives us a good idea of how each individual straw is behaving in the module. It should be pointed out that this is not a direct test for leaks; this is a test for gain variations across the straw, which is then linked to gas leaks. The impossibility to perform accurate leak tests to each individual straw in the module leaves us unable to check the correctness of our results until the module in disassembled.

D. Noise Estimate

In order to calculate an estimate of the noise in the different electronic channels, we made the following assumption:

1. The influence of the noise to the count rate followed Gaussian statistics, with the mean value located at the edge voltage.

2. The electron cluster behaves as a delta function, which means that the radius of the cluster in infinitesimally small.
3. The escaping electrons either always escape from the gas volume or get absorbed within the cluster. This means that only one electron cluster can be produced per absorbed photon.

To understand the first assumption, we have to study the influence of the noise to the count rate.

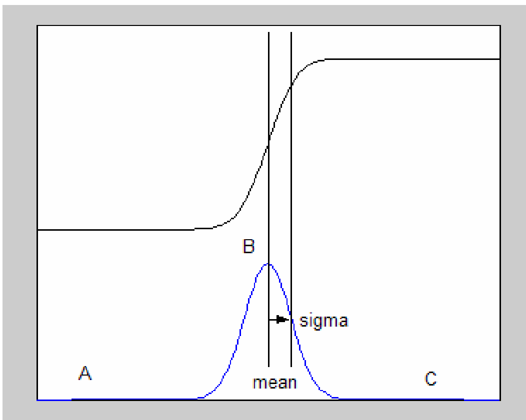

Fig. 14: Diagram showing the expected distribution of the influence of the noise on the count rate.

Figure 14 shows a diagram of the assumed distribution of the influence of the noise on the count rate. Points A, B, and C represent three different positions in the plateau. Figure 15 shows a more detailed explanation. In A, the difference between the threshold and the signal is too big for the noise to have any influence in the count rate. On the other hand in C, the signal is too large so the noise again does not affect the count rate. In B, near the edge voltage, the signal is near the threshold, and in this case the noise can have its greatest influence on the count rate.

To calculate the noise estimate we need to take into account the other contributions to the standard deviation of the plateau curve (Fit). The most important contribution comes from the statistical fluctuations in the size of the primary electron cluster. This can be easily calculated using Eq. 1, and the fact that the cluster size follows Poisson Statistics [1], then:

$$s_{cluster} = \sqrt{m} = \sqrt{226.5} = 15.05 = 6.64\%$$

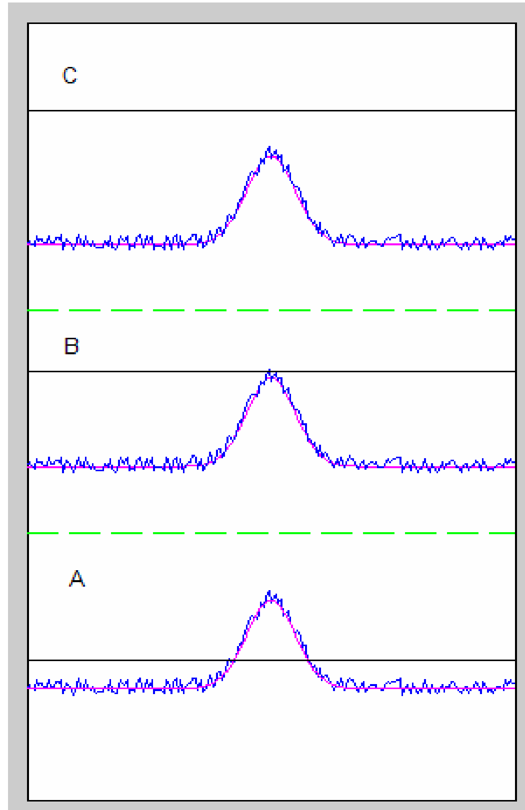

Fig. 15: Influence of the noise on the count rate

Using this value, we can calculate an estimate of the equivalent noise in Coulombs:

$$s_{noise} = \sqrt{(s_{total})^2 - (6.64)^2}$$

$$Noise = h(EV) * a * b * s_{noise} * e$$

$$h(V) = gas \quad gain \quad at \quad voltage \quad V$$

$$a = Percentage \quad of \quad total \quad charge \quad collected \quad by \quad electronics$$

$$b = \# \quad of \quad primary \quad electrons$$

$$EV = edge \quad voltage$$

$$e = charge \quad of \quad electron$$

Figure 15 shows the estimated equivalent noise for the electronic channels. The rms noise is 0.49 fC. The expected value for the noise level is 0.34 fC, as reported by creators of the board. [5]. The discrepancy in the results is a consequence of the assumptions made in the calculations. The fact that the electron cluster is not a delta function and that multiple clusters can be created as a consequence of secondary photons contribute to the statistical fluctuations. This fluctuations should be taken into account when calculating s_{noise} if more precise results are needed.

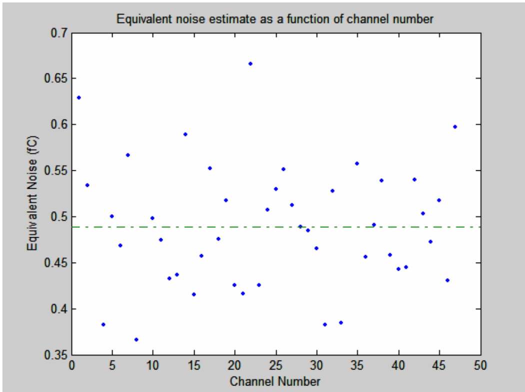

Fig. 16: Equivalent Noise Estimate in electronic channels
RMS noise = 0.49 fC

V. Conclusions

After completing the analysis of the data collected, we arrived at the conclusion that the study of the lower edge of the plateau is an effective was to investigate the efficiency and quality of the straws during the installation of the detector. The measurements that are needed to perform the analysis are fast and easy, and the results obtained are satisfactory.

The height of the plateau was found to be a good parameter to study and compare the straws quality, uniformity and efficiency in the module. Because of the dependence of this parameter with the straw position, the voltage at the edge of the plateau was found to be a better parameter to measure gain variations. The values found for the edge voltages in the module ranged from 1090 to 1110, which corresponds to gains between 1800 and 2200.

From the study of the gain variations in the straws, using measurements with the gas flowing in opposite directions, we found results that suggested leaks in four straws of the module. These results should be corroborated once the detector is disassembled. For the noise equivalent estimate, we found a value of 0.48 fC, which corresponds to an error of 41% with the reported measured value. The error in these results can lead to an estimate on the error produced by other phenomena not included in the calculations like the fluctuations in the physical size of the primary electron cluster, the production of secondary clusters produced by escaping photons, etc. Unfortunately, more measurements are needed to corroborate this. Finally, the behavior of the straws was studied as a function of the source position along the straws. There is a definite decrease in the amplitude of the signal as the source moves closer to the electronics' end of the module, but no exact conclusions were found. More measurements are needed to obtain a more complete understanding of the different processes involved, such as the signal splitting and the signal attenuation. It is necessary to perform gain calculations by measuring the amount of charge collected by the electronics in order to be able to make a more detailed study.

VI. Acknowledgements

First of all, I would like to thank my supervisor, Alan Hahn, for his guidance and support throughout the program and for making this summer a great experience for me. Also, I would like thank Penny Kasper, Bill Pritchard and John Krider for their support. Finally, I would like to thank Dianne Engram, Elliot McCrory, Dr. Davenport, Dave Peterson, Bonnie Fleming and all the people that helped me throughout the summer.

VII. References

[1] F. Sauli: 'Principles of operation of multiwire proportional and drift chambers', 1979.

[2] A. Hahn: 'Gas Gain in 4mm Straws'; BTeV-doc-448-v2 2001

[3] BTev: Proposal Update, 2002.

[4] BTeV: An Expression of Interest for a Heavy Quark Program at C0, 1997.

[5] W. Bokhari, J. Heinrich, N. Lockyer, F. M. Newcomer, R. Van Berg, H. H. Williams, M. Binkley, A. Mukherjee, K. Pitts, R. Wagner: 'The ASDQ ASIC for the Front End electronics of the COT'; CDF/DOC/TRACKING/CDFR/ 4515, 1999.