SLAC-TN-06-017

Simulation of the BaBar Drift Chamber

Rachel Anderson

Office of Science, Science Undergraduate Laboratory Internship (SULI)

University of Wisconsin - Eau Claire

Stanford Linear Accelerator Center

Stanford, CA

August 24, 2006

Prepared in partial fulfillment of the requirements of the Office of Science, Department of Energy's Science Undergraduate Laboratory Internship under the direction of Michael Kelsey and Jochen Dingfelder at the Experimental Group C, Stanford Linear Accelerator Center.

Participant: ______________________________

Signature

Research Advisor: ______________________________

Signature

Work supported in part by Department of Energy contract DE-AC02-76SF00515

TABLE OF CONTENTS

ABSTRACT

Simulation of the BaBar Drift Chamber. RACHEL ANDERSON (University of Wisconsin - Eau Claire, Eau Claire, WI 54701) MICHAEL KELSEY AND JOCHEN DINGFELDER (Experimental Group C, Stanford Linear Accelerator Center, Stanford, CA 94025)

The BaBar drift chamber (DCH) is used to measure the properties of charged particles created from e^+ e^- collisions in the PEP-II asymmetric-energy storage rings by making precise measurements of position, momentum and ionization energy loss (dE/dx). In October of 2005, the PEP-II storage rings operated with a luminosity of $10 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$; the goal for 2007 is a luminosity of $20 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$, which will increase the readout dead time, causing uncertainty in drift chamber measurements to become more significant in physics results. The research described in this paper aims to reduce position and dE/dx uncertainties by improving our understanding of the BaBar drift chamber performance. A simulation program — called GARFIELD — is used to model the behavior of the drift chamber with adjustable parameters such as gas mixture, wire diameter, voltage, and magnetic field. By exploring the simulation options offered in GARFIELD, we successfully produced a simulation model of the BaBar drift chamber. We compared the time-to-distance calibration from BaBar to that calculated by GARFIELD to validate our model as well as check for discrepancies between the simulated and calibrated time-to-distance functions, and found that for a 0° entrance angle there is a very good match between calibrations, but at an entrance angle of 90° the calibration breaks down. Using this model, we also systematically varied the gas mixture to find one that would optimize chamber operation, which showed that the gas mixture of 80:20 Helium:isobutane is a good operating point, though more calculations need to be done to confirm that it is the optimal mixture.

INTRODUCTION

The primary goal of the BaBar experiment [1] is to study particles and their antiparticles in order to understand the predominance of matter in the universe. More specifically, the purpose of BaBar is the study of B^0 and $\bar{B}^0$ meson decays to CP eigenstates so that we may understand CP-violating asymmetries. Further goals of BaBar are to identify and perform comprehensive studies of beauty and charm mesons, and tau leptons.

Inside the BaBar detector, the 9.1 GeV electron beam and the 3 GeV positron beam of the PEP-II storage rings collide with a center-of-mass energy equal to the mass of the Υ(4S) resonance (10.58 GeV). The Υ(4S) is a $b\bar{b}$ bound state which decays with equal probability into B^+B^- or $B^0\overline{B}^0$ mesons creating the ideal situation for studying B^0 and $\overline{B}^0$ meson decays.

The BaBar detector is a cylindrical detector consisting of a silicon vertex tracker (SVT), surrounded by the drift chamber (DCH), a Cherenkov Detector (DIRC), then a cesium iodide (CsI) crystal calorimeter (EMC) wrapped in the Instrumented Flux Return (IFR). Around all of this is a superconducting solenoid which produces a magnetic field of 1.5 T along the length of the chamber, the z direction. The BaBar detector reconstructs the paths of particles as they traverse the chamber, and determines their momenta. Cherenkov light from the particle's interaction in quartz bars in the DIRC provides a velocity measurement. Combined with the momentum measurement from the DCH, we can identify the different mass of the particles. Hadrons, which generally do not interact in the EMC, are filtered in the IFR for muon identification by measuring the momentum and specific ionization loss, dE/dx, using the resulting data to calculate the mass, then matching the mass to the corresponding particle.

The charged particles produced in the e^+ and e^- collisions (such as B,D, or τ) traverse the detector, ionizing the gas. The displaced electrons drift towards the sense wire, causing an electrical pulse on the wire telling us not only the wire the particle's trajectory is close to, but the time since the event was triggered (a combination of hardware and software signal which indicate that an interesting event occurred). Using a time-to-distance calibration (shown in Figure 1), we can use the time since the trigger to determine how close the particle was to the sense wire. From this information, the particle's distance from each sense wire it passed near is calculated, and the reconstruction process determines the path of the particle and the momentum.

The PEP-II accelerator operates at a luminosity of $10 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, such that it is capable of distinguishing about 3,000 events per second. However, by 2007 the BaBar team aims to be operating with a PEP-II luminosity of $20 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. In order to operate at this luminosity, the DCH must be capable of processing a greater density of events. A hindering factor is the dead time - inefficiency caused by the detectors inability to process an event because it is processing a preceding event. With the increase in luminosity, dead time will become a greater problem as not only will the event rate increase, but background noise as well.

In order to distinguish the small electrical pulses generated by charged particles passing by the DCH sense wires from other signals and background noise, the chamber must operate with a high drift velocity: the average velocity at which an ionization electron travels through a gas. This will not only decrease the dead time, but cause the ionization electrons to travel in a straighter path leading to a stronger distance to arrival time correlation. For the distance we used the distance of closest approach (DOCA), shown in Figure 2, as it is at that distance that we will get the minimum drift time. For the same reason, it is important to keep the Lorentz angle at a minimum, as it will help in spatial resolution. The Lorentz angle is the angle of the drift trajectory to the magnetic field. As the Lorentz angle increases, electron drift path curvature also increases. Finally, we want to maximize dE/dx (specific energy lost due to collisions with gas molecules) for a stronger pulse and a greater resolution.

The goal of our research is to create an accurate computer simulation of the BaBar drift chamber using a software program called GARFIELD. Once a model was established, we used

GARFIELD to fulfill the following:

- Vary the entrance angle to study its impact on drift time.
- Systematically vary the gas mixture in order to explore possible solutions that might promote a higher drift velocity, while keeping a large dE/dx, good dE/dx resolution, and minimizing the Lorentz angle.
- Compare the *t(DOCA)* correlation from BaBar to that simulated by GARFIELD.

This model will be used to validate the performance of the BaBar DCH, improve the chamber calibrations, and explore variations of chamber settings that could improve chamber operation.

GARFIELD [5] is a computer program that simulates gaseous detectors, given the complete detector definitions including gas composition, magnetic field, voltage, particle definition, and physical components. The program generates plots, histograms, and tables with electric field contours, drift velocity, Townsend coefficient (the number of electron-ion pairs formed by an electron along path of 1 cm length), diffusion coefficients (rate of electrons drifting perpendicular to electric field), Lorentz angles, as well as information on ionization clusters including their energy and the path they follow through the chamber [3]. GARFIELD can generate an arrival time histogram as well as a plot showing the relationship between the distance of the particles from the sense wire and arrival time. This data can be compared to information from the BaBar DCH to either validate its behavior or find where there might be a discrepancy.

This paper presents comparisons of the BaBar drift chamber to the GARFIELD model, as well as describes the results of varying parameters in the computer simulation.

MATERIALS AND METHODS

The BaBar drift chamber is composed of 7104 individual hexagonal cells made up of a tungsten-rhenium sense wire surrounded by a hexagon 120 μm gold-plated aluminum field wires. The cells are arranged into 40 axial and stereo layers, sectioned into 10 superlayers, layers 1 through 16 being shown on the left in Figure 3 [1].

We used GARFIELD to model a section of the fourth superlayer of the DCH, also shown in Figure 3. Consistent with the BaBar DCH, we specified a sense wire diameter of 20 μm and a field wire diameter of 120 μm, both with a length of 275 cm. The sense wires have a tension of 30 g while the field wires have a tension of 190 g. The field wires were grounded, and the sense wires had a voltage of 1930 V. The magnetic field was set in the $+z$ direction with an amplitude of 1.5 T. The drift gas mixture was set to 80% He and 20% iC_4H_{10} with 3500 ppm H_2O and 80 ppm O_2. For the simulated particle that traverses the modeled fourth superlayer, we specified a positive pion (π^+) with a kinetic energy of 500 MeV. Within the GARFIELD program, we used a program called HEED [4] to simulate the ionization of the gas molecules by a pion to create clusters. We asked that the drift electrons with enough energy to cause secondary ionizations (i.e. delta electrons) be taken into account. For the calculations and plots, we focused on an area of 2.8 cm by 2.8 cm centered on sense wire number four of layer 15, located near the center of the superlayer, in order to avoid fringing effects. It was specified that the electrons start to drift from the surface of the sense wire, in reverse, as though they had a positive charge. In this way the drift line plots show the origin of all electrons that eventually hit the wire, as shown in Figure 4. Within GARFIELD, a program called MAGBOLTZ [2] is used to calculate drift velocity and Lorentz angles for electrons in gas mixtures under the influence of electric and magnetic fields.

The different parameters and their values for our most accurate model of the DCH are shown in Table 1.   We were able to use GARFIELD to generate histograms, plots, and tables presenting the simulation of the BaBar drift chamber. GARFIELD output includes a print of the section of the wire configuration (Figure 3), a contour plot of the electric field, and a plot of electron drift lines (Figure 4). GARFIELD also plots histograms of clustering information, including the distance between electron and track, number of electrons per cluster, number of clusters on the track, distance between cluster and track, energy per cluster, energy lost, and number of electrons on the track. From the timing section, GARFIELD plots histograms for both the arrival time of the earliest electron on the sense wire (Figure 5) and the arrival time of all electrons. For the gas study, GARFIELD's output includes graphs of the drift velocity, diffusion coefficients (both transverse and longitudinal), Townsend coefficient, attachment coefficient, and Lorentz angle (Figure 5) all with respect to the electric field. With our DCH model, we are able to use this data to learn more about the BaBar DCH.

Our first study was on the effect of the entrance angle on drift velocity. We used GARFIELD to generate clusters of electrons on points 0.5 cm from the sense wire. We then rotated from $-180°$ to $180°$ in 100 steps around the sense wire, each time calculating the angle and the drift time of an electron starting at that point. While HEED generates a more physical clustering model, these fixed points were a simplification that we were able to use to compare the drift velocity of electrons starting on tracks $0°$ to $360°$ from the r-axis (Figure 2).

For the second goal of this research, to find a better system design, we used the chamber model and varied the helium-isobutane gas mixture from 100:0 to 70:30 to explore the effects of isobutane. Although a gas mixture of 100:0 would be disastrous for the chamber (allows discharges at low voltages), it is used as a comparison. We compared the drift time, Lorentz angle (both in Figure 5), and dE/dx (Figure **??**) for the different gas mixtures. We computed the drift time from GARFIELD's timing command, looking at the fastest electron to reach the sense wire from a track with a DOCA of 0.8 cm (Figure 7). For this, GARFIELD used 1000 iterations, of which we used the fastest. The Lorentz angles are compared in Figure 5. Finally, to study the difference in specific ionization energy loss, we used the total-energy-lost clustering-histogram from the drift section of GARFIELD. For this calculation, GARFIELD also used 1000 iterations, from which we computed an 80% truncated mean (the smallest

80% of results). The track we used was 1.6 cm in length, and had a DOCA of 0.48 cm (Figure 7), as shown in Figure 7. From these comparisons we were able to determine the optimal gas mixture from among those studied.

With this DCH model established, we compared it to the BaBar DCH. Using GARFIELD we generated a plot of the distance between a particle and a sense wire with respect to time. To do this, we considered tracks with entrance angles ψ from the sense wire, then rotated it from $0°$ to $90°$ in increments of $5°$. Fore each ψ we computed the drift time for tack DOCAs spanning the cell in 0.1 cm steps. From this data we made a time-to-distance plot which we compared to the corresponding calibration used by the BaBar reconstruction software.

RESULTS

Figure 8 displays the impact that entrance angle can have on drift velocity. Though the overall velocity only changes within 0.9 ns, it does show a sinusoidal relation, shown by the graph on the left. The plot on the right shows the time to DOCA relationship for entrance angles of $-30°$, $0°$, $30°$, and $90°$. Near the sense wire (DOCA = 0 cm) the electric field is symmetric, so all curves look the same. However, near the field wires, where the electric field is spatially asymmetric, the drift velocities vary and the shape of the *t(DOCA)* curves change.

The results of the gas study show the importance of the balance between arrival time, Lorentz angle, and dE/dx. As the percentage of isobutane increased, the drift velocity decreased as there were more interactions between particles, shown by the histogram in Figure 5. For the drift velocity, it appears that the 70:30 gas mixture is the best choice as it has the smallest arrival time. However, the Lorentz angle graph shows that as the isobutane increases, so does the Lorentz angle for BaBar's operating voltage of 1930 V. For the 70:30 gas mixture, the Lorentz angle is greatest, while that for the 80:20 mixture is better. The Lorentz angle for the 90:10 mixture is the best, however due to its higher drift time it would not be the optimal choice. It is left to dE/dx to decide between the 80:20 and the 70:30.

The final part of the gas study was the comparison between dE/dx for different gas mixtures. From the graphs in Figure 6, we see that as isobutane increases, dE/dx also increases, as isobutane is a quencher and neutralizes the ions. Once again the 70:30 gas mixture appears to be the best, as it has the desired maximum dE/dx. Finally, the dE/dx resolution plot shown on the right in Figure 6 shows that the 70:30 gas mixture also has the best resolution. However, as isobutane is highly flammable, the more isobutane is in the mixture, the more hazardous it would be to work with. It is the balance between arrival time, Lorentz angle, and dE/dx that leads to the conclusion that the 80:20 gas mixture used in BaBar is a good operating point as it keeps the Lorentz angle lower. The difference in Lorentz angles for the 80:20 and the 70:30 gas mixtures is approximatley 2°, therefore, if we were to change the gas mixture our results say that the 70:30 mixture would be ideal.

The results of the time-to-distance calibration comparison are shown in Figure 1. For an entrance angle of 0° (particle is passing straight through the chamber), the GARFIELD simulation is a very good match. For the 30° and -30° entrance angles, there is a clear discrepancy between the GARFIELD prediction and BaBar's calibration. Finally, for an entrance angle of 90° (particle is traveling in a loop through the chamber), the BaBar calibration breaks down noticeably.

DISCUSSION AND CONCLUSIONS

We were able to successfully model the performance of the BaBar drift Chamber. The arrival time vs. entrance angle study showed that near the sense wire the different time-to-distance correlations from different entrance angles behaves the same, as the electric field is symmetric. However, near the field wires, where the electric field is spatially asymmetric the *t(DOCA)* curves vary significantly with the entrance angle. From the gas study, it was shown that a gas mixture of 80:20 Helim:Isobutane is a good operating point. The 80:20 mixture is a good balance between the arrival time, the Lorentz angle and dE/dx. While the 70:30 mixture has the minimum arrival time, and the best dE/dx resolution, its Lorentz angle is greater than that for the 80:20 mixture. Balancing these three, the 80:20 mixture that the BaBar DCH uses appears to be a good operating point. However, were the gas mixture to be changed, a 70:30 isobutane mixture is recommended. For the time-to-distance calibration comparison, we found a good agreement between the calibrated real data and the simulation for 0°, but found that the calibrations for non-zero entrance angles have systematic discrepancies which could be affecting reconstruction.

Future studies include understanding the discrepancy between the BaBar time-to-distance calibration and the GARFIELD simulation, as well as fixing those discrepancies which are negatively affecting reconstruction, in order to improve tracking efficiency. Furthermore, now that a computer simulation for the BaBar DCH has been constructed, future studies can be done to explore variations of chamber settings that could improve operation.

ACKNOWLEDGMENTS

The author would like to thank Michael Kelsey, Jochen Dingfelder, and Adam Boyarski from Experimental Group C for your guidance, as well as Rob Veenhof for help with GARFIELD, and the U.S. Department of Energy Science Undergraduate Laboratory Internship Program for the opportunity to work at SLAC.

REFERENCES

[1] BaBar Collaboration, *The BaBar detector*, Nuclear Instruments and Methods in Physics Research **A** 479, 1-116 (2005).

[2] Biagi, Stephen, *Magboltz: Transport of electrons in gas mixtures*, http://consult.cern.ch/writeup/magboltz, (2005).

[3] Kleinknecht, Konrad, *Detectors for particle radiation*, Cambridge University Press, Cambridge (1987).

[4] Smirnov Igor, *Heed: Interactions of particles with gases*, CERN Computer Newsletter 226, 13 (1996).

[5] Veenhof, Rob, *Garfield - simulation of gaseous detectors*, CERN Computer News Letter 2000-001 Vol. XXXV, issue no 1 (2000).

FIGURES

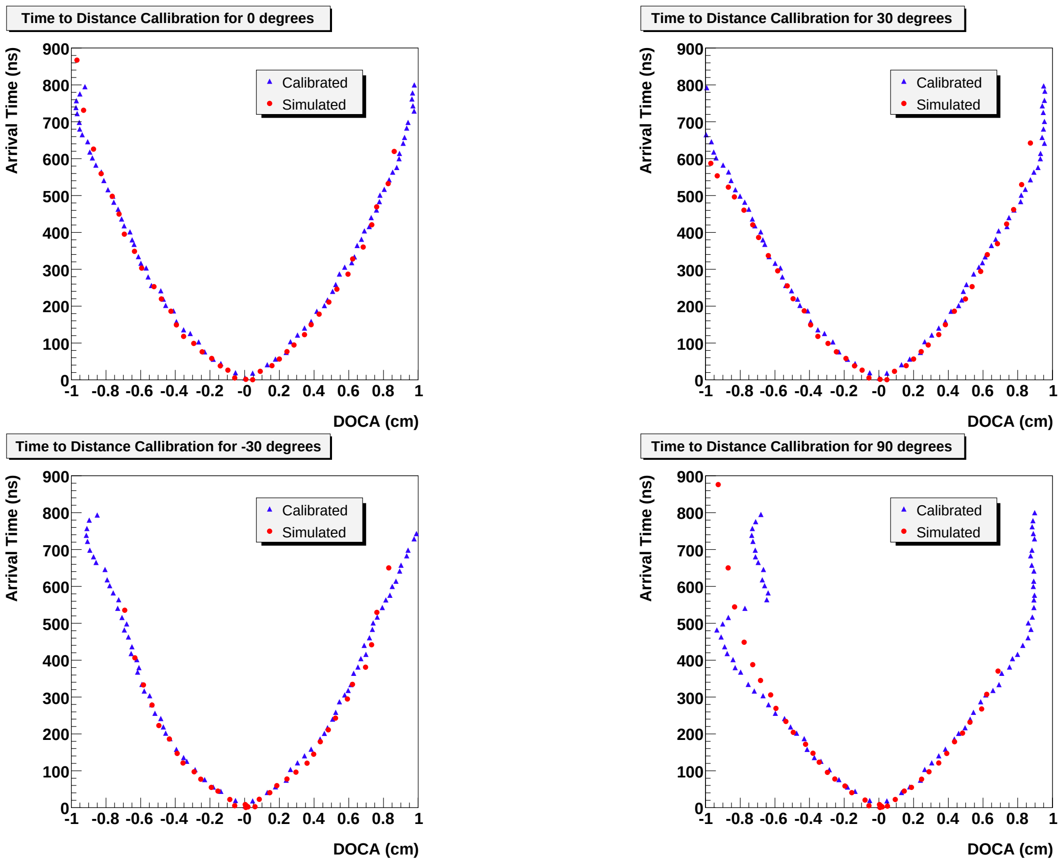

Figure 1: time-to-distance calibration for the DCH: GARFIELD's simulation (red circles) vs. BaBar's time-to-distance calibration (blue triangles) for four different entrance angles $(-30^\circ, 0^\circ, 30^\circ, 90^\circ)$.

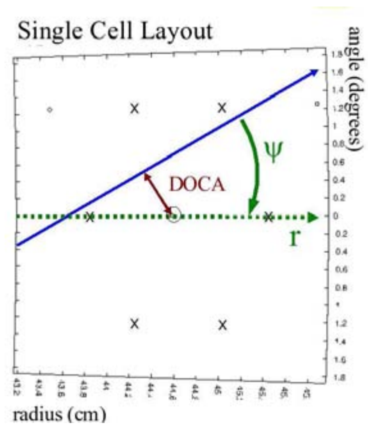

Figure 2: Particle track distance of closest approach (DOCA) and entrance angle, ψ. $\mathbf{r}$ is the vector from center of detector through sense wire.

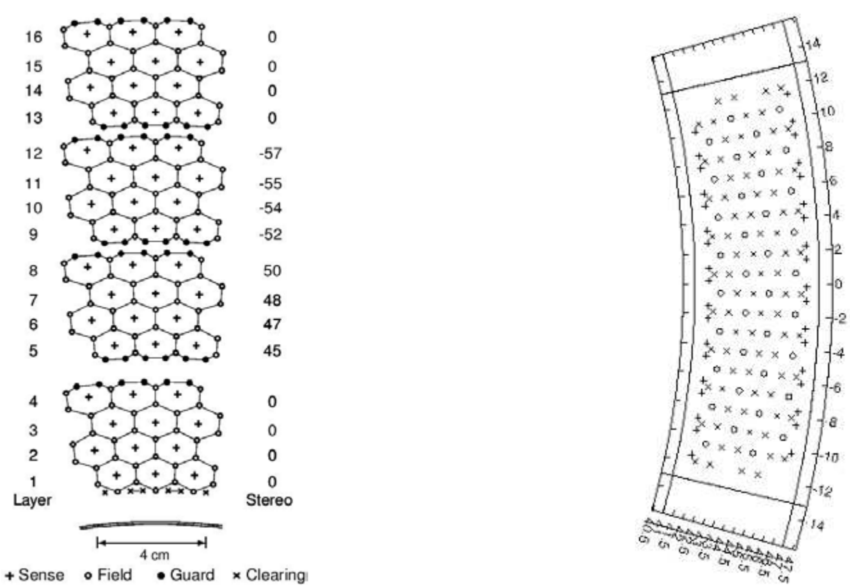

Figure 3: On the left is the wire configuration for BaBar DCH section. On the right is the cell entered into GARFIELD drift chamber model, with ($\mathbf{r}$,ϕ) coordinates shown. Sense wires are shown by circles, field wires are shown by the x's, and guard wires are crosses.

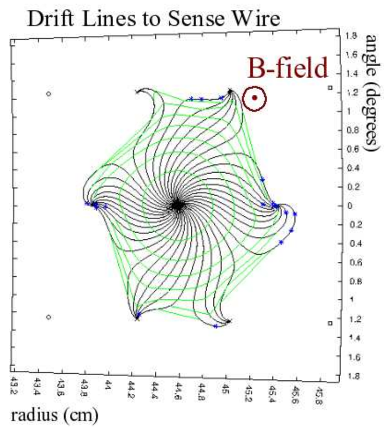

Figure 4: Drift lines and isochrones around sense wire, with 1.5 T magnetic field.

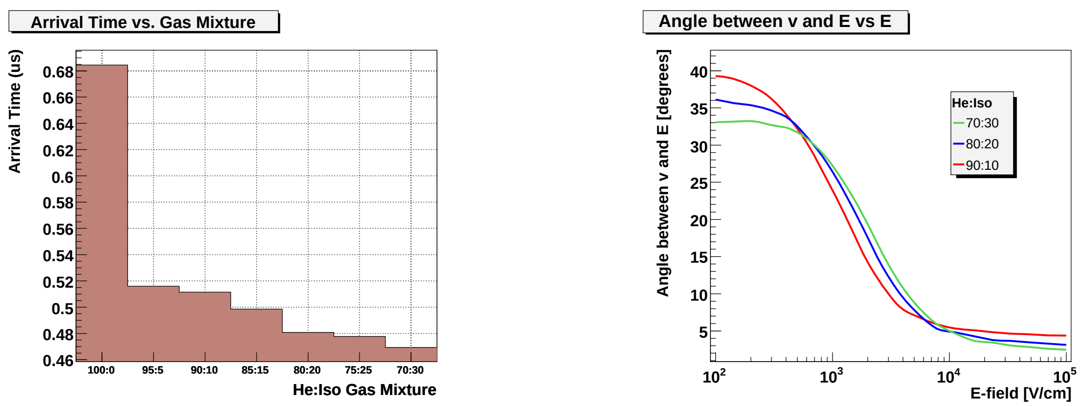

Figure 5: Histogram on left shows the arrival time for different Helium:Isobutane proportions, where 80:20 is BaBar's gas mixture. Graph on the right shows the Lorentz angle as a function of electric field (for a magnetic field of 1.5 T). BaBar operates with an electric field of 2×10^3 V/cm.

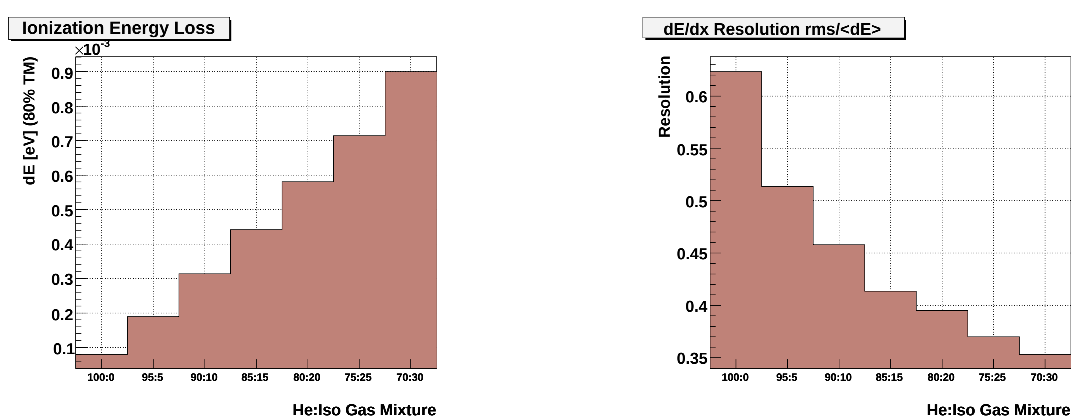

Figure 6: Histogram on left shows dE/dx for different gas mixtures from He:Iso 100:0 to 70:30, where 80:20 is BaBar's operating point. The histogram on the right shows the dE/dx resolution, RMS(dE/dx)/¡dE/dx¿, for the test particle.

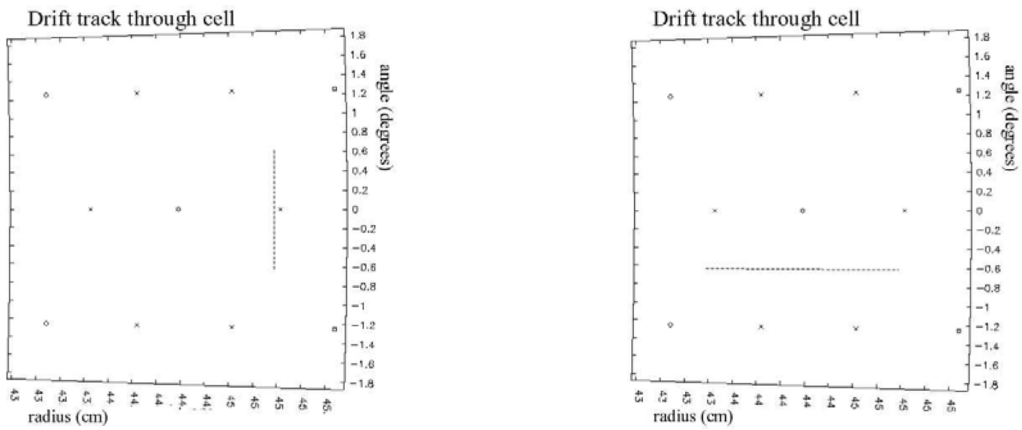

Figure 7: On the left is the track that the arrival time was calculated from. On the right is the track on which dE/dx is calculated.

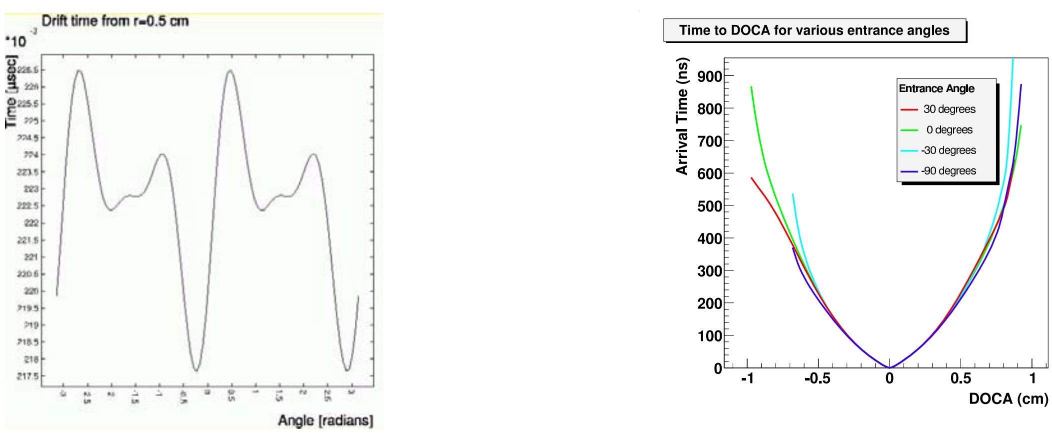

Figure 8: Drift time vs. entrance angle of electron. The graph on the left is of a particle starting a distance of 0.5 cm from the sense wire for all entrance angles. The graph on the right is of particles starting between -1 cm and 1 cm from the sense wire at entrance angles $-90°$, $-30°$, $0°$,and $30°$.

TABLES

Parameters	**Value**
sense wire diameter	0.0020 cm
field wire diameter	0.0120 cm
wire length	275 cm
sense wire voltage	1930 V
field wire voltage	0 V
sense wire density	106.95 g/cm^3
field wire density	14.94 g/cm^3
sense wire tension	30 g
field wire tension	190 g
magnetic field	1.5 T
He	80 %
iC_4H_{10}	20 %
H_2O	3500 ppm
O_2	80 ppm

Table 1: The table shows the variables and their values as entered into GARFIELD.