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Improved particle identification using cluster counting in a full-length drift chamber prototype

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ABSTRACT

Single-cell prototype drift chambers were built at TRIUMF and tested with a ~210 MeV/c beam of positrons, muons, and pions. A cluster-counting technique is implemented which improves the ability to distinguish muons and pions when combined with a traditional truncated-mean charge measurement. Several cluster-counting algorithms and equipment variations are tested, all showing significant improvement when combined with the traditional method. The results show that cluster counting is a feasible option for any particle physics experiment using drift chambers for particle identification. The technique does not require electronics with an overly high sampling rate. Optimal results are found with a signal smoothing time of ~5 ns corresponding to a ~100 MHz Nyquist frequency.

1. Introduction

This paper describes the development and testing of a prototype drift chamber whose purpose is to evaluate the feasibility of a “cluster-counting” technique [1] for implementation in a high luminosity e^+e^- experiment. Cluster counting is expected to improve particle identification (PID) by reducing the effect of fluctuations in drift chamber signals. These are due to gas amplification and the fluctuation in the number of primary electrons per ionization site. There may also be improvements in tracking resolution, but this is left for a later study. The requirement of fast electronics and larger data sizes may make the technique impractical in terms of capital costs, available space near the detector, and computing power. To date the technique has not been deployed in an operating experiment. This work demonstrates that a cluster-counting drift chamber is a feasible option for an experiment such as Super*B* [2,3]. Super*B* was cancelled after the experiments described in this paper, but the results are applicable to any drift chamber that is used for particle identification. The design of our prototype chambers was strongly influenced by the demands of Super*B*, which are described in the Technical Design Report [4].

1.1. Drift chambers

Drift chambers are general-purpose detectors that can track and identify charged particles [5,6]. They consist of a large volume of gas with instrumented wires held at different voltages. When charged particles move through the chamber they ionize the gas particles. The electrons from these primary ionizations drift towards the wires held at high positive voltage, while the ions drift towards the grounded wires. The sense wires are very thin (~20 μm), such that the strong electric field accelerates the electrons enough to cause further ionization near the sense wire. The new electrons ionize further into an avalanche, which is registered as an electronic signal on the sense wire. The amplification of the low-integer number of primary ionization electrons into a detectable signal on the wire is called the gas gain.

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The energy loss of a heavy ($m \gtrsim 1\ \mathrm{MeV}/c^2$) charged particle from primary ionizations depends on its speed, as given by the Bethe formula [7] and various corrections [8]. The speed measurement is combined with the independent momentum measurement from tracking, giving the particle's mass, which is a unique identifier. To measure speed, we measure or estimate a quantity proportional to the number of primary ionizations. A traditional drift chamber accomplishes this by measuring the total ionization per unit length of the track, which is proportional to the integral of the electronic signal on the sense wires belonging to a track. The theoretical probability distribution function for the total ionization is a Landau distribution, which has an infinite mean and standard deviation [6]. The consequence is that if one takes the average of a number of samples (e.g. 40 measurements of deposited charge in a track), the resulting distribution is non-Gaussian and is dependent on the number of samples taken. Instead of the mean of the distribution, one can use the most probable value for the total ionization. This is accessed by a truncated mean technique. Our truncated mean procedure is described in Section 5.2.

1.2. *Cluster counting*

The conventional technique described above is sensitive to gas gain fluctuations as well as the statistical fluctuations in the number of primary electrons produced in each ionization event. Moreover, the truncated mean procedure that is typically used discards a substantial fraction of the available information. None of these disadvantages exist if the number of primary ionizations can be measured more directly.

1.2.1. *Technique*

The cluster-counting technique involves resolving the cluster of avalanching electrons from each primary ionization event. This is done by digitizing the signal from the sense wire in each cell and applying a suitable algorithm. The rise time of the signal from a cluster is approximately 2 ns, so electronics with sufficiently high bandwidth are required.

In principle, clusters can be detected as long as they do not overlap completely in time. This can happen irrespective of the electronics involved due to the probabilistic nature of the ionization process. Overlapping clusters are more likely for highly oblique tracks. Complex algorithms which consider signal pulse heights might disentangle even overlapping clusters, but the algorithms tested in this work do not.

An optimal algorithm would have a high efficiency for identifying true clusters and a low rate of reporting false clusters (due to noise for example).

1.2.2. *PID*

In traditional drift chambers using the integrated signal, the signal amplitude is determined by the convolution of the probability of primary ionization, the number of primary electrons produced, and the variations in gas gain. This results in a long-tailed distribution that is typically dealt with by the truncated mean procedure. Conversely, if clusters are perfectly identified, then the only variation is from the primary ionization, which is a Poisson process. No cluster counts need to be discarded to allow for a proper statistical treatment. In reality some counted clusters will be missing or fake, the rate of these being caused by gas gain fluctuations, noise level, and the time separation capabilities of the electronics. The idea is that the sensitivity to these effects is small. The difficulty arises from the need to optimize an arbitrarily complex cluster-counting algorithm.

A difficulty with both charge integration and cluster counting is the presence of δ-rays [6]. These are electrons produced in primary ionizations that travel far in the gas before further ionizing, such that they create their own separate ionization cluster. The production of δ-rays at a given momentum depends only on the particle speed ($\propto 1/\beta^2$) [8]. This inflates the charge integral and the cluster count with only a weak dependence on the species of the original particle, the result is a decreased PID resolution in general. The presence of δ-rays is one of the reasons why a truncated mean is used in the charge integration method. While cluster counting is also affected by δ-rays, the effect is less pronounced, allowing all of the data to be used.

1.2.3. *Cluster timing*

Any cluster-counting algorithm that uses a digitized signal is able to report not only the number of clusters in a cell, but also the arrival time of each of those clusters. In the oversimplified case of a linear and homogenous drift velocity and infinite cells, the average spacing in time between consecutive clusters would simply be proportional to the inverse of the number of clusters in the cell. In a more realistic scenario, the average spacing between clusters is useful information that is not one-to-one with the number of clusters. We can exploit the lack of perfect correlation and use the cluster timing information to further improve our ability to identify particles.

1.2.4. *Tracking*

For tracking, cluster counting may also improve performance, but in a much lesser degree and more subtle manner than as for PID. A traditional drift chamber uses only the arrival time of the overall signal in determining the distance of closest approach from a sense wire. Unfortunately this arrival time measurement is vulnerable to noise, gas gain fluctuations (small initial clusters may be missed), etc. If the first few clusters are resolved, then while the first cluster arrival time is still the primary datum, the second cluster arrival time can be used as a consistency check. If the second cluster arrives much too late, then the chance that the first cluster was a fake is greater, so a smaller statistical weight can be assigned to that cell when reconstructing the whole track. This paper deals only with the PID improvements and does not address tracking.

2. Apparatus

In this section we describe the prototype drift chambers that were built, the custom signal amplifiers and the various types of cables that were tested. We also describe the experimental setup in the test beam, the data acquisition system, and the devices used for external PID and triggering.

2.1. *Prototype drift chambers*

We built two nearly identical full-length (2.7 m) single-cell drift chambers, called chamber *A* and chamber *B* (Fig. 1). The only difference between the two chambers is the diameter of the sense wires: 20 μm for Chamber *A* and 25 or 30 μm for Chamber *B*. More details about the wires are given below.

The wire layout creates a square cell 15 mm wide in a 10×10 cm cross-section casing (for a gas volume of $2.7 \times 10^4\ \mathrm{cm}^3$). Fig. 2 shows a cell diagram including the dimensions and wire locations. The aluminium casing of the chambers has five large windows on two sides of the cell to allow particles to enter and exit unimpeded. The windows are made of thin ($\sim 20\ \mu\mathrm{m}$) aluminium, protected by aluminized Mylar.

Different amplifiers are mounted on the endplates of the drift chambers, connected directly to the sense wires. The amplifiers vary in their gain, input impedance, and bandwidth. They are described in more detail in Section 2.2.