NON-MAGNETIC MOMENTUM SPECTROMETER BASED ON FAST TIME-OF-FLIGHT SYSTEM

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Abstract

A new generation of large-area, low cost time-of-flight detectors with time resolutions ≤ 10 ps and space resolutions ≤ 1 mm is being developed for use in nuclear and particle physics experiments, as well as for medical and industrial applications. Such detectors can serve as the basis for measuring momenta without requiring measurement of curvature in magnetic fields. Factors affecting measurement accuracy and simulation results are presented.

INTRODUCTION

The development of fast, large area, low cost time of flight detectors with excellent spatial resolution is developing rapidly. Prototype detectors with areas of ~1 m^2 are expected to become available for testing and early applications in the next year or two. One of the applications that is attractive for early testing is the use in muon cooling experiments. The University of Chicago and Muons, Inc. are members of a multi-institutional collaboration LAPPD [1] that is developing fast TOF detectors based on micro-channel plates and fast electronics to realize the objectives of time resolutions ≤ 10 ps and space resolutions ≤ 1 mm for several applications. It is expected that time resolutions as low as 1 ps will be achievable as new materials and electronics become available. A description of the detectors and the readout electronics is given in another paper presented in this conference [2].

CONCEPTS

The time of flight (TOF) between two detectors is related directly to the particle's velocity, v = s / t. The momentum is simply derived from the flight time (t) to travel the distance (s). For relativistic particles the velocity approaches c with increasing momentum, and thus t must be measured more precisely to determine v to a given precision.

TOF Resolutions and Momentum Resolutions

For a relativistic particle the momentum and the error on the momentum determination in terms of the time of flight as follows.

$$P = \gamma\beta m_0,\ \Delta P = m_0\beta\gamma^3\sqrt{(\frac{\Delta s}{s})^2 + (\frac{\Delta t}{t})^2}\ , \quad (1)$$

P and m_0 are the momentum and rest mass of particle, γ and β are the Lorentz factor and velocity in terms of velocity of light, and Δs and Δt the spatial and time resolutions for the detectors, respectively. Figure 1shows the momentum resolution for a non-magnetic TOF spectrometer when the particles hit the center of the both detectors, which are separated by 2 m and have time resolution (σ_t).

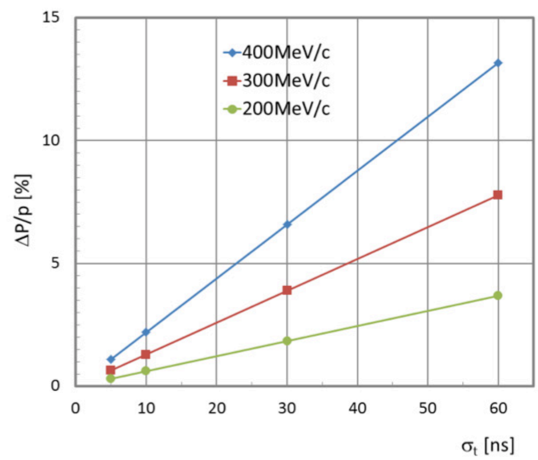

Figure 1: Momentum resolution of non-magnetic TOF spectrometer with various TOF resolutions (σ_t) for incident beam momenta of 200, 300 and 400 MeV/c.

The momentum resolution has a position dependence on TOF counters as shown in Fig. 2. When the particle hits the edge of detector, the flight path length is even longer and the momentum resolution becomes better than the case of hitting the center.

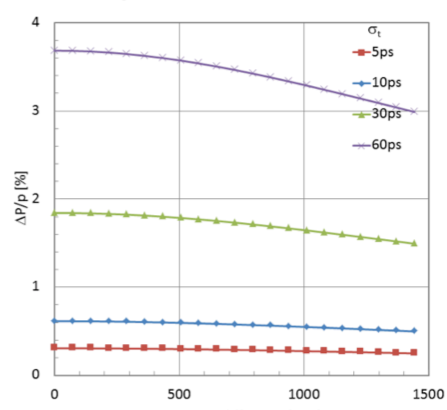

Figure 2: Position dependence of momentum resolution on TOF counters for 200-MeV/c beam. The position difference is defined as $\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$, when a particle hits ($x_1$, y_1) and (x_2, y_2) on the detectors.

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Typical plastic counters with photomultipliers have a TOF resolution about 60 ps, while micro-channel plate (MCP) based detectors can achieve better than 10 ps resolution. With more precise timing detectors the use of time-of light to measure momenta or to identify particles becomes feasible over a broader set of experiments and applications.

Factors that Limit or Degrade the Resolution

The factors that limit the resolution attainable in fast timing detectors are being actively studied by many groups at this time. In practice there are several contributing factors, in addition to the time resolution of the detectors and the speed of the electronic of the readout systems. A new workshop on this subject is scheduled in the near future [3]. The composition of the detector planes is important for the spectrometer application. It is desirable to minimize the amount of material in the detectors to reduce scattering, energy loss, and straggling. There are tradeoffs between signal magnitude and material thickness. For example, in the LAPPD designs the thickness of the window that serves as a Cherenkov radiator produces more light for thicker windows, but that also increases the scattering and energy loss.

The cross-section of fast TOF detector that uses micro-channel plates (MCP) to amplify the signals, such as in reference [1], is shown in Figure 3. The incident particle produces Cherenkov radiation in the entrance window. The light is converted to electrons in a photo-cathode deposited on the back surface of the window, and the signal is amplified by a pair of MCP layers to which a high voltage is applied. The signal is received by an anode shown in green, which is part of a transmission line across the exit window. The signal is transmitted by the transmission line to the readout electronics. The windows contribute most of the mass of the unit, as the MCP layers are porous and have low density. For structural integrity there may be a backing plane of low density foam or honeycomb material. In some configurations there may be a PC board and electronics on the back plane.

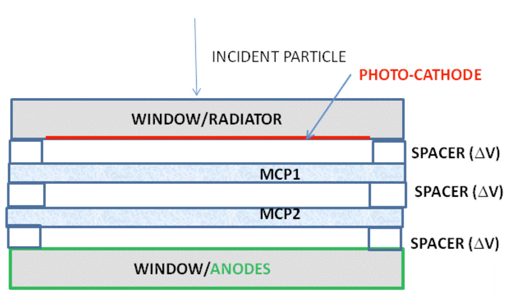

Figure 3: Cross section of a typical MCP-based planar TOF detector. Windows are shown in gray, MCPs are blue, photo-cathode and anode layers are red and green, respectively.

For a panel of the type shown in Figure 3, the space resolution attainable depends on the details of the signal development and capture. For example in Figure 1 the effective point at which the signal is encoded or it may be at the photo-cathode, in the MCP planes, or at the anode plane, or at the mid-plane of the transmission line between the anode and the ground. These points vary with the angle of the trajectory of the particle.

Another factor that may limit the determination of the momentum is the thickness of the exit window, particularly for intermediate planes in a multiple plane system. There is additional energy loss in the back window that is not directly taken into account if the momentum is based on the measurement at the anode plane. Corrections can be made for the passage of the particle through the remaining material, but there is statistical uncertainty due to energy straggling. In addition the multiple scattering in the remaining material alters the exit angle from the angle determined from the point encoded in the TOF counter. We will address these issues in a future report.

STUDY OF RESOLUTIONS OF TOF SPECTROMETER

We have performed simulation studies of the resolution of non-magnetic TOF spectrometer using the GEANT4-based G4beamline simulation package [3].

Time of Flight Spectrometer

An ideal TOF spectrometer is comprised of two TOF planes, each of which measures the time and position of the particle's trajectory at their respective planes. In practice additional measurement planes are needed to provide redundancy and, if the incident particles are unstable, decays in flight will occur between the planes, which can be rejected on the quality of the fit. A more practical non-magnetic TOF-based spectrometer is shown in Figure 4. The spectrometer has an upstream arm and a downstream arm. Each arm consists of two TOF detectors and two sets of idealized "wire" planes, each set recording x and y space coordinates and but no time information. In an experiment, between the upstream arm and the downstream arm, the system under test is installed. The system to be tested could be e.g. a target for measuring scattering or reaction cross sections or a muon cooling channel.

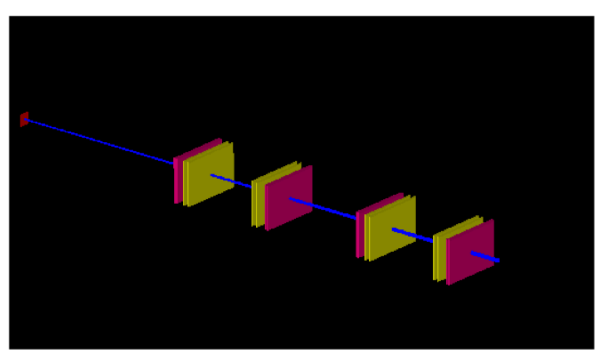

Figure 4: Two arm non-magnetic TOF spectrometer. The red planes are TOF detectors with time and space outputs.

The yellow planes record spatial coordinates, but provide no timing information.

The resolution obtained by simulation for one arm has been computed for a beam of 200 MeV/c muons is presented here for 1 m separation between TOF planes. Each TOF planes has been assigned 10 ps time resolution and 0.3mm space resolution. The wire planes have been assigned 0.3 mm resolution. The material assigned to the TOF planes is 1 cm of glass. Track fitting is done using the G4beamline function. The fitting procedure is described in Reference [2].

The results of the fits are shown in Figure 5.The time resolution is obtained from the distribution of the difference between the true time and the time resulting from the fit. The observed time resolution is 15.8 ps, slightly larger than the input resolution of 10 ps, due to the dispersion in arrival times caused by energy loss in the material in the TOF planes. The momentum resolution, computed downstream of the spectrometer arm shown in Figure S1b, is 2.4 MeV/c, or 1.2%. This is consistent with the calculated value in Figure1.There is a slight shift of the momentum resolution peak, due to the amount of material in the exit window of the TOF plane that is accounted for in the "true" track but not in the fitted track.

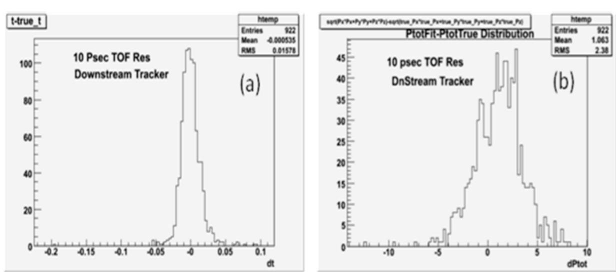

Figure 5: Time and momentum resolutions for the downstream arm of the spectrometer setup.

Reducing Errors in Momentum Determination

Energy loss straggling is a contributor to the error in determining the momentum with a time of flight spectrometer. One means to reduce the effects of the straggling tail that produces a non-Gaussian momentum distribution is to identify events in which an electron is knocked out of the material by the incident particle, causing a larger energy loss to the muon. We ran a simulation of the passage of 200 MeV/c muons passing through a series of detectors. By placing virtual detectors after the last of the 4 detectors we were able to capture events in which there was an electron in addition to the muon. The following semi-log momentum distributions are shown in Figure 6 for muons and electrons.

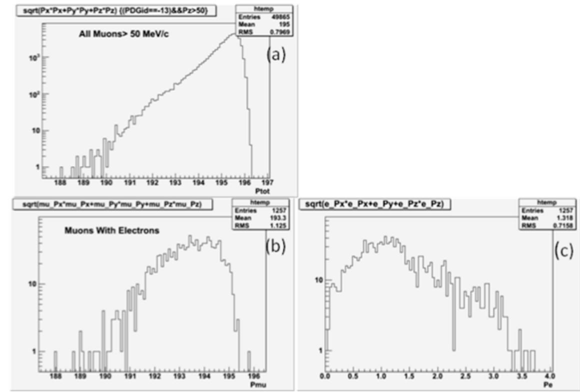

Figure 6: Momentum distributions for (a) all muons, (b) muons with an electron detected, (c) electrons.

In about 2.5% of the cases there is an electron detected. The electron momentum distribution ranges out to ~4 MeV/c. The momentum spectrum of the muons with an electron in Figure 6(b) differs considerable from that of all muons in Figure 6(a). Detailed comparison of the figures shows that the low momentum tail (P< 192 MeV/c) is made up almost entirely of muons in which there is an electron present., and the distribution. Thus the elimination of events with delta rays can reduce the tail of the muon momentum distribution.

SUMMARY

We have presented some of the concepts for a non-magnetic time of flight spectrometer and estimations of the resolutions attainable, as well as factors affecting the resolutions. We have shown resolutions for a simulation of a spectrometer and one method of improving the resolutions, by detecting delta rays and reducing the tail of the momentum loss distribution.

REFERENCES

[1] Large-Area Picosecond Photo-Detectors Project, http://www.psec.uchicago.edu/

[2] R. Abrams, et al, "Fast Time of Flight System for Muon Cooling Experiments", Paper MOP040, PAC11 Conference

[3] Workshop on Factors that Limit Time Resolution in Photodetectors, Chicago, Illinois, April 28-29, 2011, http://psec.uchicago.edu/workshops/fast_timing_conf_2011 .

[3] http://g4beamline.muonsinc.com