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Signal processing for picosecond resolution timing measurements

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ABSTRACT

The development of large-area homogeneous photo-detectors with sub-millimeter path-lengths for direct Cherenkov light and for secondary electrons opens the possibility of large time-of-flight systems for relativistic particles with resolutions in the picosecond range. Modern ASIC techniques allow fast multi-channel front-end electronics capable of sub-picosecond resolution directly integrated with the photo-detectors. However, achieving resolution in the picosecond range requires a precise knowledge of the signal generation process in order to understand the pulse waveform, the signal dynamics, and the noise induced by the detector itself, as well as the noise added by the processing electronics. Using the parameters measured for fast photo-detectors such as micro-channel plates photo-multipliers, we have simulated and compared the time resolutions for four signal processing techniques: leading edge discriminators, constant fraction discriminators, multiple-threshold discriminators and pulse waveform sampling.

1. Introduction

The typical resolution for measuring time-of-flight of relativistic particles achieved in large detector systems in high energy physics has not changed in many decades, being on the order of 100 ps [1,2]. This is set by the characteristic scale size of the light collection paths in the system and the size of the drift paths of secondary electrons in the photo-detector itself, which in turn are usually set by the transverse size of the detectors, characteristically on the order of 1 in. (85 ps). However, a system built on the principle of Cherenkov radiation directly illuminating a photo-cathode followed by a photo-electron amplifying system such as a Micro-Channel Plate Photo-Multiplier (MCP-PMTs) [3] with characteristic dimensions of 10 μm or less, has a much smaller characteristic size, and consequently a much better intrinsic time resolution [4–6].

Time-of-flight techniques with resolution of less than several picoseconds would allow the measurement of the mass, and hence the quark content, of relativistic particles at upgraded detectors at high energy colliders such as the Fermilab Tevatron, the LHC, Super-B factories, and future lepton-colliders such as the ILC or a muon-collider, and the association of a photon with its production vertex in a high-luminosity collider.[1]

Other new capabilities at colliders would be in associating charged particles and photons with separate vertices in the two-dimensional time-versus-position plane, and searching for new heavy particles with short lifetimes [7,8]. The difference in transit times over a path-length of 1.5 m, typical of the transverse dimension in a solenoidal collider detector such as CDF or ATLAS, is shown in Fig. 1. Many other applications with different geometries, such as forward spectrometers, would have significantly longer path-lengths, with a consequent reach in separation to higher momenta, as can be scaled from the figure.

There are possible near-term applications of fast timing requiring resolutions of several picoseconds in smaller area systems ($\simeq 0.001$–$1\,m^2$), such as missing-mass searches for the Higgs at the LHC [9], and non-magnetic spectrometers for the development of six-dimensional phase-space muon cooling [10]. There are likely to be applications in other fields as well, such as measuring longitudinal emittances in accelerators, precision time-of-flight in mass spectroscopy in chemistry and geophysics, and applications in medical imaging such as time-of-flight for Positron Emission Tomography (PET) applications.

At lower time and position resolution, the same techniques could be used for instrumenting the surfaces of large-ring imaging water Cherenkov counters, in which measurement of both the

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[1] At a high-luminosity machine such as the LHC there are many collisions per beam crossing, making associating photons from a Higgs decay with a specific vertex difficult, to pick one example. This application would require the conversion of the photon and a simultaneous precision measurement of the time and position.

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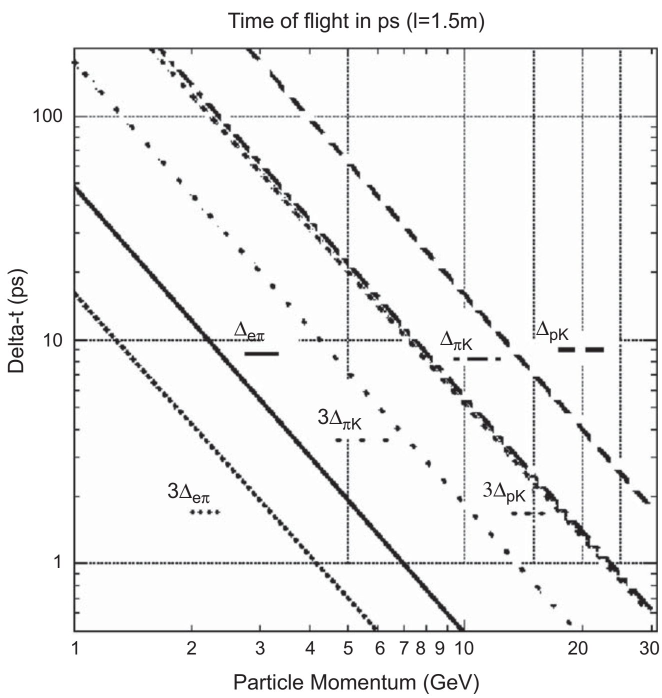

Fig. 1. The difference in times over a path-length of 1.5 m for electrons (i.e. zero time delay relative to the speed of light) versus pions, pions versus kaons, and kaons versus protons, as a function of the charged particle momentum. The time resolutions necessary for a 3-σ separation versus momentum are also shown.

position and time-of-arrival of Cherenkov photons would allow reconstruction of track directions and possibly momenta [11].

In order to take advantage of photo-detectors with intrinsic single photo-electron resolutions of tens of picoseconds to build large-area time-of-flight systems, one has to solve the problem of collecting signal over distances large compared to the time resolution while preserving the fast time resolution inherent in the small feature size of the detectors themselves. Since some of these applications would cover tens of square meters and require tens of thousands of detector channels, the readout electronics has to be integrated via transmission lines with the photo-detector itself in order to reduce the physical dimensions and power, increase the analog bandwidth, improve readout speed, and provide all-digital data output.

There are a number of techniques to measure the arrival time of very fast electrical pulses [12–15]. Typically one measures the time at which the pulse crosses a single threshold, or, for better resolution, the time at which the pulse reaches a constant fraction of its amplitude [16]. An extension of the threshold method is to measure the time that a pulse crosses multiple thresholds [17].

A recent development is the large-scale implementation of fast analog waveform sampling onto arrays of storage capacitors using CMOS integrated circuits at rates on the order of a few GSa/s. Most, if not all of them, have actually 3-dB analog bandwidths below 1 GHz [18–21]. The steady decrease in feature size and power for custom integrated circuits now opens the possibility for multi-channel chips with multi-GHz analog bandwidths, and able to sample between 10 and 100 GHz, providing both time and amplitude after processing. Assuming that the signals are recorded over a time interval from before the pulse to after the peak of the pulse, with sufficient samples fast waveform sampling provides the information to get the time of arrival of the first photo-electrons, the shape of the leading edge, and the amplitude and integrated charge. While other techniques can give time, amplitude, or integrated charge, fast sampling has the advantage that it collects all the information, and so can support corrections for pileup, baseline shifts before the pulse, and filtering for noisy or misshapen pulses. In applications such as using time-of-flight to search for rare slow-moving particles, having the complete pulse shape provides an important check that rare late pulses are consistent with the expected waveform.

The outline of this note is as follows: Section 2 describes the four techniques for determining the time-of-arrival of an electrical pulse from a photo-detector. Section 3 describes the input signal parameters of the simulation program used for the comparisons, and the parameters used for each of the four methods in turn. Section 4 presents the results and the methods and parameters to be used in real systems. The conclusions and summary are given in Section 6.

2. Timing techniques

Present photo-detectors such as micro-channel plate photo-multipliers and silicon photo-multipliers achieve rise-times well below 1 ns [22–24]. Ideal timing readout electronics would extract the time-of-arrival of the first charge collected, adding nothing to the intrinsic detector resolution. Traditionally the best ultimate performance in terms of timing resolution has been obtained using constant fraction discriminators (CFDs) followed by high precision time digitization. However, these discriminators make use of wide-band delay lines that cannot be integrated easily into silicon integrated circuits, and so large front-end readout systems using CFDs to achieve sub-ns resolution have are not yet been implemented.

Several other well-known techniques in addition to constant-fraction discrimination have long been used for timing extraction of the time-of-arrival of a pulse:

(1) single threshold on the leading edge;
(2) multiple thresholds on the leading edge, followed by a fit to the edge shape;
(3) pulse waveform sampling, digitization and pulse reconstruction.

Applying a fixed threshold to the leading edge, which is a one-parameter technique, suffers from a dependence of the extracted time with the pulse amplitude, even for identical waveforms. In addition, this method is sensitive to baseline shifts due to pileup, the overlap of a pulse with a preceding one or many, a situation common in high-rate environments such as in collider applications. Also, for applications in which one is searching for rare events with anomalous times, the single measured time does not give indications of possible anomalous pulse shapes due to intermittent noise, rare environmental artifacts, and other real but rare annoyances common in real experiments.

In contrast, constant fraction discrimination takes into account the pulse amplitude. The most commonly used constant fraction discriminator technique forms the difference between attenuated and delayed versions of the original signal, followed by the detection of the zero crossing of the difference signal. There are therefore three parameters: the delay, the attenuation ratio, and the threshold. These parameters have to be carefully set with respect to the pulse characteristics in order to obtain the best timing resolution.

The multiple-threshold technique samples the leading edge at amplitudes set to several values, for instance at values equally spaced between a minimum and a maximum threshold. The leading edge is then reconstructed from a fit to the times the pulse reaches the thresholds to extract a single time as characteristic of the pulse. As in the case of constant fraction discrimination, if the pulse shape is independent of amplitude, the reconstructed time