Development of a 10 Picosecond Time of Flight Counter

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1 Introduction

We propose to develop at University of Texas at Arlington (UTA) an extremely fast (order of 10 ps) time-of-flight (TOF) counter for measuring the arrival time of beam particles in fixed target experiments or particles scattered at small angles in high energy hadron colliders. The proposed detector will be a small Cerenkov counter coupled to a micro-channel plate photomultiplier tube (MCP-PMT).

Research to develop this type of detector, dubbed PICO-TOF for both its size and performance, is of general interest for several reasons:

- PICO-TOF would be useful for any collider that is currently equipped with or plans to have proton detectors (this includes all accelerators except electron-only machines). The LHC experiments ATLAS and CMS are potential customers for such a detector. The time measurement from counters on either side of the interaction point would provide a rather precise determination of the event vertex, allowing rejection of background from multiple proton-proton (or $p\bar{p}$) interactions in the same bunch crossing [1]. For example, as discussed below, a time resolution of 10 ps would yield a vertex uncertainty of 2.1 mm, allowing substantial rejection of this pile-up background, depending on the width of the luminous region. These benefits would greatly enhance the physics prospects for a recently proposed upgrade to ATLAS and CMS consisting of near beam silicon detectors 420 m [2] upstream and downstream of the central detectors. Near beam detectors 220 m from the interaction point (Totem and a possible ATLAS upgrade) would benefit from fast timing detectors as well.

- PICO-TOF could also be used for a next generation $ep$ collider for photo-production events, where the proton and electron are scattered at small angles. Interesting all neutral final states like $\gamma\gamma$ would not have tracks and consequently no reconstructed vertex. A PICO-TOF detector would improve the mass resolution by determining the vertex for this class of events.

- These detectors could be used in fixed target experiments or test beams to tag the different incoming beam particles (hyperons or kaons, for example). By measuring the time at two points on the track, it would be possible to measure the velocity and thus the mass of the beam particle.

- Finally R&D efforts focus on improvements to MCP-PMT’s which are a critical element
of future “traditional” TOF counters, those concerned with particle identification in final states rather than a vertex measurement.

In the body of this proposal we discuss the physics motivation for developing PICO-TOF. We discuss Cerenkov detectors, issues involving MCP-PMT’s, previous work in this area, and potential improvements. We discuss the electronics required for fast timing and present our recent test beam results. Finally we present plans to build and test two different PICO-TOF detectors, combined with different types of MCP-PMT’s generously provided by Burle Industries, Inc. [3] and Hamamatsu, Inc. [4], the industry leaders in advanced photo-detectors.

2 Background and Recent Accomplishments

The PICO-TOF Collaboration consists of the UTA group led by the P.I. Andrew Brandt, and groups from University of Alberta led by Jim Pinfold, University of Louvain led by Krzysztof Piotrzkowski, and Fermilab led by Michael Albrow. The P.I. has a long history of developing detectors for tagging forward protons, from the UA8 experiment where he was lead graduate student, to instigating and leading the DØ Forward Proton Detector. The UTA group includes Jia Li, an engineer/physicist who will spend part of his time on the project and several graduate and undergraduate students. The UTA facilities, outlined in supplemental documents include a state-of-the-art new research building. Pinfold’s group is building the ATLAS LUCID Cerenkov detector and has experience with pulsers and fast timing circuits. They will be contributing electrical engineering expertise and a senior graduate student to the project. Piotrzkowski also has a long history of detector development and experience with the ZEUS proton tagger. Louvain has built Cerenkov detectors for HARP, and has an experienced electrical engineer and mechanical and electrical shops. Finally, Michael Albrow of Fermilab, a long-time leader in proton tagging is also contributing his expertise to the project. The group was formed due to common interest in exclusive Higgs production (discussed below), which led us to the pursuit of a fast timing detector. We have already successfully completed our first test beam effort, demonstrating the efficacy of this collaboration. We have also benefited from a good working relationship with Jerry Va’vra, one of the leading authorities on fast timing, who is consulting on our project.

As part of my effort to develop fast timing expertise I attended the “Pico-Sec Timing Hardware Workshop” in Chicago in November 2005 [5], traveled to SLAC in March 2006 to meet Jerry Va’vra, hosted the “10 Picosecond Workshop” at UTA in April 2006 [6], and traveled to the Burle plant in Pennsylvania to meet with the micro-channel plate developers. I received funding to support my initial endeavors in fast timing from the Texas Advanced Research Program [7], primarily for student support.

3 Physics Motivation for Improved TOF Counters

3.1 Exclusive Higgs Production

The new physics discovery potential of forward proton tagging at LHC energies has become a topic of great interest over the past few years, largely motivated by recent theoretical studies on diffractive Higgs production [8]. Proton detectors could be especially useful in complementing the standard channels for the low mass Higgs search (or other new physics), due to the potentially excellent missing mass resolution of events with two tagged protons. FP420 [2], a joint ATLAS/CMS R&D effort, has been investigating the feasibility of such an upgrade, which has been encouraged by the LHCC due to their recognition of its physics potential.
Figure 1 shows a schematic diagram of the process of interest, the so-called central exclusive production process, $pp \rightarrow ppM$. Due to the details of the color flow, the only final state particles are the protons and the decay products of the $M$ state, which are separated by rapidity gaps (absence of particles) from the scattered protons.

An example of the $M$ system is a standard model Higgs boson, for which the decay products could consist of two $b$-quark jets, and no other activity. The process is attractive for two main reasons:

1. If the outgoing protons remain intact and scatter through small angles, then, to a very good approximation, the central system must be produced in a spin 0, CP even state, allowing a clean determination of the quantum numbers of the observed resonance.

2. As a result of these quantum number selection rules, coupled with the excellent mass resolution on the central system achievable from proton tagging, signal to background ratios of greater than unity are predicted for Standard Model Higgs production (11 signal over 3 background for a 120 GeV Higgs boson in a luminosity of 30 fb$^{-1}$) at the LHC [9], competitive with other single channels. Much larger significances are obtained for the lightest Higgs boson in certain regions of the MSSM parameter space [10].

The reason for these large signal to background ratios is that exclusive $b$-quark production, the primary background in light Higgs searches, is heavily suppressed due to the quantum number selection rules. By measuring azimuthal asymmetries in the tagged protons it is possible to directly probe the CP structure of the Higgs sector, previously thought to be possible only at a future linear collider [11].

In addition to Higgs physics, proton tagging also provides a unique opportunity to investigate the full strong interaction sector both within and beyond the Standard Model, from heavy hadron resonances to gluinos and radions. Indeed any new state that couples to gluons and has the appropriate quantum numbers could be studied with proton taggers.
Clearly, if the theoretical estimates are correct and the installation of forward proton detectors with appropriate acceptance is feasible, then the physics case is extremely strong. A number of workshops have been held over the last couple of years to address the issues. Early studies of this subject gave wildly varying cross sections, differing by many orders of magnitude, but recent theoretical progress has reduced these uncertainties to the factor of 2–3 range for a 120 GeV Standard Model Higgs boson. The largest uncertainties in the signal cross section predictions come from three sources: the Sudakov factors (arising from the requirement that the process be exclusive—no radiation from the exchanged gluons); the gap survival factor (the rate of destruction of the outgoing protons by multi-parton interactions); and the knowledge of the off-diagonal unintegrated gluon distributions. Improved estimates of background rates are needed and this work is already well underway. A primary uncertainty in the background estimates comes from the experimental definition of the exclusive process where an optimal definition should be able to eliminate the potentially large background from non-exclusive diffractive processes, and the contribution from higher order exclusive production.

UTA has been active in the area of background rejection from multiple interaction events, not only using the timing detectors discussed in the proposal, but also using various kinematical cuts to ensure consistency between the tagged protons and the central system. Brandt currently leads this effort and is supervising UTA Ph. D. student Arnab Pal, who has performed the first pile-up rejection studies using the ATLAS fast detector simulation [12], following up on the generator-level Monte Carlo work of Andy Pilkington [13]. These studies show the backgrounds appear to be under control for luminosities approaching $10^{34}$ cm$^{-2}$ s$^{-1}$.

Recent results from CDF provide strong evidence for the exclusive process in the dijet and di-photon channel [14] at the predicted cross section level [15], providing an important validation of the theoretical predictions. Work continues in this area at both CDF and DØ, which has proton taggers on both sides allowing the definitive observation of exclusive events.

The position detectors for forward proton taggers are expected to be comprised of “edge-less” silicon [16], since acceptance as near as possible to the beam is critical. The timing detectors for forward proton taggers have traditionally been scintillators with standard PMT's giving resolution of no better than 200 ps. A PICO-TOF detector would provide background suppression enabling an array of new physics possibilities as discussed above.

3.2 Particle Identification

3.2.1 Large Area Time-of-flight

Time-of-flight (TOF) counters are typically used as part of the particle identification capability of multi-purpose particle physics detectors. Particle identification with a TOF counter stems from a measurement of the time of arrival of the particle at the detector relative to the collision time. Given a momentum ($p$) measurement of the particle from its bending in the magnetic field, the mass $m$ (and identity) of the particle can be determined from $m = \frac{p}{c} \times \sqrt{\frac{c^2 \Delta t^2}{L} - 1}$, where $L$ is the path length. Figure 2, from a study for the Run II CDF TOF detector [17], shows the difference in time-of-flight between kaons ($K$), pions ($\pi$), and protons ($p$) as a function of momentum. This detector clearly complements the particle identification from $dE/dx$ measurements. The $K/\pi$ separation is critical for reconstructing $B$-hadron decays, allowing the determination of the $b$-quark flavor, which in turn is crucial for CP violation studies. A time resolution of 100 ps, the design goal of the CDF Run II TOF detector, gives a $2\sigma K/\pi$ separation for $p < 1.6$ GeV/c. Improving the time resolution to 10 ps would result in a corresponding factor of 10 improvement in the separation significance shown on the right hand axis of Fig. 2 for fixed $p$ and also provide separation to much higher momenta.
Figure 2: The difference in time-of-flight between kaons (K), pions (π), and protons (p) as a function of momentum. The right-hand side y-axis gives the significance for resolving different particles as a function of momentum. The separation from a dE/dx measurement is also shown.

Improved time resolution would thus increase the efficiency of heavy-flavor-tagging. In particular, a K meson with a displaced vertex is likely to come from B or D-meson decays. This will have consequences for measurements of BB and DD mixing as well as rare B decays. Knowing the particle type could help in setting the jet energy scale. This would be particularly important for Linear Collider detectors which will use particle flow information.

Time-of-flight measurements are interesting beyond separating π, K, and p [18]. They can also be used to search for exotic, heavy particles. There are several, well-motivated examples where long-lived particles arise in new physics models. This can occur if a charged-neutral particle pair arises, so that they are degenerate at tree-level, but split in mass by radiative corrections. In this case, the slightly-heavier, charged particle can have a substantial lifetime. In various models of Supersymmetry the lightest neutralino and the lightest chargino are of nearly degenerate mass. The chargino could be rather long-lived, or could decay within the detector. An accurate TOF could thus play an important role in the discovery of new physics.

While the detectors being developed here are not directly applicable to the large area TOF’s discussed above, the knowledge gained through this proposal will lead to improved MCP-PMT’s through our connections with Burle, which would likely be employed by large scale TOF’s.

3.2.2 Test Beam

The same particle identification techniques discussed above would be directly applicable to test beam experiments. Frequently test beams are composed of a mixture of protons, pions, and other particles. A PICO-TOF detector that could be put in the beam would be able to identify the beam particles, allowing a selection of the type of beam particle desired by the individual experiment.
4 Cerenkov Detectors and Timing

4.1 Cerenkov Detectors

In the arena of high energy physics, time-of-flight detectors employing quartz Cerenkov radiators read out by MCP-PMT’s have achieved the best reported timing resolutions ($\approx 5$ ps) [19]. Detectors which make use of the Cerenkov effect are generally favored for fast timing applications due to the prompt, essentially instantaneous emission of radiation as a charged particle travelling at a substantial fraction of the speed of light $v = \beta \times c$ enters a medium with a relatively large index of refraction ($n$), such that the particle exceeds the speed of light in that medium ($v > c/n$). Figure 3 shows a 2-dimensional slice of the wavefront of the emitted cone of Cerenkov photons.

![Figure 3: A schematic diagram showing the emission of Cerenkov radiation as described in the text.](image)

From Fig. 3 we can see that $\cos \theta_c = 1/\beta n$, where $\beta \approx 1$ for modern accelerators. An expression for the number of photons emitted as a function of wavelength is

$$\frac{dN}{d\lambda} = 2\pi\alpha L \sin(\theta_c)^2 / \lambda^2$$

(1)

where $\alpha$ is the fine structure constant $1/137$, and $L$ is the length (in cm) of the radiating material [20]. Integrating this expression one can obtain the number of photons/cm, which is strongly dependent on the wavelength range, which in turn depends on the radiative material and the details of the MCP-PMT (specifically the PMT window composition).

4.2 Micro-channel Plate Photomultiplier Tubes

A micro-channel plate is a lead glass structure with an array of holes (pores) typically of diameter 10–25 $\mu$m that serve as miniature electron multipliers [21]. They were originally developed as amplifiers for image intensification devices, but their sensitivity to charged particles and energetic photons has made them very useful in many fields including particle physics. The schematic diagram in Fig. 4 shows an incoming photon which is converted to electrons in the photocathode. The electrons then shower in the micro-channel plates (this diagram shows two plates) typically giving a gain of about $10^6$. The shower is then deposited on the anode, which may be segmented to provide a multi-anode pixel capability.
4.3 Timing of Cerenkov Detectors

Three main factors affect the time resolution of a detector:

1. The first is the spread in the arrival time of the radiation to the photocathode, which depends on the type and geometry of the detector.

2. The second factor is the time resolution of the MCP-PMT. This is dominated by the transit time spread (TTS), or jitter, associated with the PMT itself ($\sigma_{TTS}$). The time it takes from the creation of a photo-electron to the production of a signal will vary slightly from trial to trial. Some of this variation comes from the differences in path length of the first photo-electron, but most arises from uncertainties inherent in the PMT. The best PMT’s currently on the market have transit time spreads of 25–30 picoseconds. The ultimate resolution of the PMT will in principle be given by $\sigma_t = \sigma_{TTS}/\sqrt{N}$, where $N$ is the number of photons accepted by the PMT.\(^1\)

3. Last, but not least, is the downstream electronics, typically consisting of an amplifier, discriminator, and TDC (time-to digital converter). It is important to have a good and constant signal shape with a fast and constant rise time. If leading edge timing is used it is important to have signals with essentially constant amplitude, or the time resolution will be degraded. Constant Fraction Discrimination (CFD) would overcome the problem of varying signal amplitude and/or rise time to a large extent achieving a comparable time resolution to a leading edge discriminator. Although it is more difficult to set up a CFD it is more robust in a real experimental situation where there is usually some pulse amplitude and rise time variation. Finally, for precision TOF timing one has to equip the front-end readout with a TDC that has a correspondingly precise time resolution, while minimizing the noise of the entire circuit.

\(^1\)In certain applications, path length variation as the electrical signal travels through the anode to a central collector can also have an impact on the tube’s timing resolution. This effect can be minimized by using an appropriate multianode design, and is not a factor in our resolution, since we separately measure each pixel time.
4.4 MCP-PMT Vendors

The two major developers of MCP-PMT’s are Burle [3] and Hamamatsu [4]. Hamamatsu has concentrated on small active area (11 mm diameter) tubes consisting of a single channel. Burle’s tubes are large (50 mm$^2$) and have options of 4, 64, or 1032 pixels. While the best reported results are for the Hamamatsu tubes, $\sigma_{TTS} < 30$ ps [19], the limited area, lack of pixelation, and relative high cost render them less interesting for most applications.

Burle is understandably eager to capitalize on this situation and has proposed several upgrades to improve their performance. The primary improvement is to reduce the pore diameter from 25 to 10 microns. Preliminary results of $\sigma_{TTS} = 32$ ps have been obtained using a 10 $\mu$m prototype (85012-501) [22]. They also plan a model with a reduced gap between the photocathode and the MCP from 6 mm to less than 1 mm to reduce the amount of recoil electrons which give a long tail to the timing distribution. This effect has already been studied with a special “dropped faceplate” version of the 25 $\mu$m pore tube 85011-430 [22], but not with the 10 $\mu$m version. Burle has already provided the UTA group with two standard 25 $\mu$m tubes and one 10 $\mu$m tube, and will provide other prototypes as they become available, including tubes with a factor of 10 enhanced current capability for rate and aging studies. Hamamatsu has provided two 6 $\mu$m tubes to the Louvain group.

4.5 Current R&D Efforts

We have identified three major areas of effort in the development of fast timing counters:

- The goal of the pioneering Nagoya group [19] is to develop a Cerenkov ring imaging detector for particle identification for a potential upgrade of the Belle detector. Their requirements are a time transit spread of $\sigma_{TTS}$ in the 50 to 100 ps range in a magnetic field of 1.5 T. They performed a thorough evaluation of several different MCP-MPT tubes and were able to achieve a single photon resolution $\sigma_{TTS} \approx 30$, using a laser setup and a Hamamatsu 11 mm diameter tube with 10 $\mu$m pore diameter. Furthermore, using the MCP-PMT alone as a detector in a 3 GeV/c pion beam, they obtained $\sigma_t = 14$ ps, with the improvement due to photon statistics from Cerenkov radiation produced in the quartz window of the tube. Ultimately they achieved a time resolution of about 5 ps (!) using a quartz block attached to an MCP tube, again placed directly in beam as shown in Fig. 5, with the time resolution dominated by the readout electronics. They found significant magnetic field dependence of the gain, and consequently timing, of the Burle tubes (presumably due to the larger 25 $\mu$m pore size).

- SLAC R&D is also focussed on development of a Cerenkov ring imaging detector for particle identification for a potential upgrade of a B-factory detector, in this case a new version of DIRC for a possible BaBar upgrade [22]. Measuring single photons to better than a 100 ps allows correction for the chromatic error contribution to the Cerenkov angle measurement in their 4 m long fused silica bars. This level of timing resolution allows a color tag, which has never been done and would help suppress background, ultimately improving $\pi/K$ separation from 3–4 GeV/c to 6–8 GeV/c. They used a pulsed laser to test Burle 10 and 25 $\mu$m pore MCP-PMT’s, performing detailed uniformity and timing studies. As shown in Fig. 6, they found very good uniformity of response in the central 36 mm$^2$ of the 50 mm$^2$ PMT, with variations of about 20% (about 50% over the whole tube) [22]. The timing studies yield similar results as the Nagoya group with respect to $\sigma_{TTS}$, and they also established that the dropped faceplate removed much of the recoil electron effect in the 25 $\mu$m tube.
• The University of Chicago R&D has a long term goal of obtaining one ps resolution with a large area TOF counter for the purpose of superior particle identification [23]. This detector would be essentially the equivalent of an upgraded large area CDF TOF counter. They would use Burle MCP-PMT’s with many pixels, but with a much smaller pore size, down to 2 $\mu$m, would be required to achieve their timing goals. They would use the tubes themselves as detectors, as in one of the Nagoya tests. Their work has focussed on simulations and developing the electronics needed for superior time resolution. The time frame for their detector development is much longer than the one to two year timescale of our proposal.

We note that all the previous work has been devoted to studies aimed at future TOF counters for particle identification for large area TOF counters, and does not address the needs of near beam detectors (e.g. you cannot put your PMT in a 7 TeV proton beam!). They have demonstrated the value of a fast laser setup for understanding details of the MCP-PMT performance, but also that a test beam is needed to understand the detector performance. Finally these studies show that smaller pore tubes must be developed and tested.

4.6 PICO-TOF Details

A precise time-of-flight counter is an important component any future proton tagger, since it could provide background rejection from pileup events (multiple proton-proton interactions in the same bunch crossing), which will be prevalent at high luminosity accelerators. Consider an event with a central massive system and two low angle protons, one each in the forward and backward direction. It is possible to measure the vertex associated with the massive system using the central tracker $z_{CT}$ with a negligible uncertainty on the several $\mu$m scale. Measurements of $T_R$ and $T_L$, the time of hits in the PICO-TOF counters to the right and left of the interaction region, respectively, also yield a vertex $z_{FP} = c(T_R - T_L)/2$. The uncertainty in this vertex position is $\delta z_{FP} = c\delta(t)/\sqrt{2}$, where $\delta(t)$ is the time resolution of a single counter; for $\delta(t) = 10$ ps we obtain $\delta z_{FP} = 2.1$ mm. If $|z_{CT} - z_{FP}| > \delta z_{FP}$, we would assume the vertices are not from the
same event and reject the event as pileup background. We note that the DØ Run I luminosity monitor scintillation counters [24] using standard PMT’s obtained a timing resolution of about 200 ps, leading to a vertex resolution ($\delta z$) of about 4 cm.

We have calculated the background rejection for the three primary background scenarios, shown schematically in Fig. 7. Given the expected $\sigma_z = 5.3$ cm width of the LHC vertex distribution, we would be able to reject 97.4%, 97.8%, and 95.5% of the three background types respectively, assuming a one $\sigma$ cut on $\delta z = 2.1$ mm ($\delta t = 10$ ps). Table 1 gives the background rejection for the three cases in Fig. 7 as a function of detector time resolution $\delta t$. Case (a) is expected to be the dominant background for most physics processes of interest, and its magnitude is much better known than the other two processes, which have not been accurately measured. We note that in case (a) and (c) $z_{FP}$, the vertex reconstructed from the time measurements, is actually a false vertex, since the protons did not come from the same vertex. The rejection is worst for case (c) due to the correlation of the two vertices, whereas case (b) has the best rejection, since both protons come from a single vertex that is distinct from $z_{CT}$. Simulations have confirmed rejection factors of 30 to 40 for typical luminosities at the LHC.

A similar calculation could be done for any other accelerator with the rejection factor a function of the width of the vertex distribution and the time resolution of the detector (for example, such a detector at the Tevatron would have a rejection greater than 99% due to the 25 cm vertex width). Clearly, a PICO-TOF detector would provide a critical component of background rejection complementing kinematical constraints from correlations between the protons and the central system.

A consideration in the detector design is whether a single timing measurement is adequate or whether segmentation in $z$ (parallel to the beam) or $x$ (perpendicular to the beam in the horizontal plane) is desirable. Segmentation in $z$ gives several timing measurements on the same track, which is likely preferable to one measurement, depending on the level of noise and random

Figure 6: Relative response in the single photon mode of the Burle 64-pad MCP-PMT, using the SLAC laser diode setup at 632 nm. The solid lines indicate the approximate borders between pads.
Figure 7: A schematic diagram of pileup backgrounds to central exclusive production: (a) three interactions, one with a central system, and two with opposite direction single diffractive protons (b) two interactions, one with a central system, and the second with two opposite direction protons (c) two interactions, one with a central system and a proton, the second with a proton in the opposite direction.

hits in the detector. It is possible that the gain in precision from multiple measurements is negated by fluctuations due to the corresponding decrease in photon statistics for any individual measurement. Segmentation in $x$ allows for the separate timing of more than one proton in the same detector, which could become a significant advantage at the highest instantaneous luminosities, when in addition to fake events from pileup, multiple protons in the same detector will become an issue. At the LHC, approximately 1% of interactions have a diffractive proton in the acceptance of a detector at $z = 420$ m [2], which implies an extra proton in the detector in 30% of events at peak luminosity. Simulations of the distance from the beam, $x$, of diffractive protons at $z = 420$ m, indicate that $x$ segmentation will be valuable at high luminosity.

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Table 1: Background rejection for the three cases in Fig. 7 vs. time resolution $\delta t$. 
4.6.1 QUARTIC

UTA has taken a lead role in the development of a PICO-TOF detector. Figure 8 shows different views of the first version of “QUARTIC,” a Quartz Timing Counter. It consists of a 4x8 array of 6 mm$^2$ square rods of fused silica (which is similar to quartz but has better transmission properties [25]) connected to a MCP-PMT. The dimensions were chosen to match the pixel size of the Burle 64 channel tube; eventually Burle may construct a sufficiently fast 1032 pixel tube, which would allow finer $x$ segmentation. Figure 8(c) shows the detector oriented at the average Cerenkov angle ($\sim 50^\circ$) with a proton passing through all eight $z$ segments for a given $x$, providing eight separate time measurements along the track. Photons are continuously emitted along the path, and the most prompt photons will travel straight down each bar. Photons emitted with an angle greater than the critical angle $\theta_{\text{crit}} = \sin^{-1}(1/n)$ will be reflected one or more times and also arrive at the PMT (total internal reflection), but have a longer path length and thus arrive later. It is possible to accept the light emitted at smaller angles (which will arrive even later), by aluminizing the bars.

A UTA group consisting of the P.I., two undergraduate students and a graduate student have been studying the QUARTIC detector. The undergraduate students have evaluated the light yield of this detector, obtaining about 820 photons produced per 6 mm bar for a wavelength range from 180–700 nm, the advertised range of sensitivity for the Burle tubes. We note this is consistent with the predictions of Ref. [19] (380 photons for 4 mm of quartz) given the effective material with the QUARTIC orientation is about 8 mm, combined with a slightly larger wavelength range. We note that the number of accepted photons per bar will only be about 100 due to a collection efficiency of 60% (roughly the ratio of pore area to surface area in the MCP) and to the quantum efficiency which is about 20% over the low to intermediate wavelength range, but decreases at high wavelength [26]. The students have also developed a ray tracing program to enable timing studies and detector optimization and have evaluated the background rejection. Initial studies showed that the wavelength dependence of the index of refraction caused an unacceptable spread in the arrival times as the range of arrival times between red and ultra-violet light was about 60 ps for the original “long bar” design. We consequently adopted a “mini-bar” approach, using shorter bars with air light guides to improve the performance.

Figure 9 shows the calculated arrival time for the accepted photons for a 3 cm mini-bar with a 6 cm air light guide after quantum efficiency and collection efficiency are applied. The rise time is about 3 ps with about 7 accepted photons expected in the first 20 ps. The long tail is due to photons that have many reflections as they travel down the bar.

We have begun a full GEANT simulation to aid in detector optimization. Figure 10 shows a first results from the long bar simulations: the left plot shows a proton passing through a fixed $x$ in the center of the detector for the case where the detector is aluminized, while the right plot shows the case of cladding, where some of the light escapes.

We constructed a pre-prototype consisting of four mini-bars with aluminized air light guides for a Fermilab test beam run in Summer 2006. UTA purchased the mini-bars and designed and built the aluminum boxes for housing the detectors. Alberta built the air light guides and their engineers assembled the detectors at Fermilab, where they were mounted in the test beam area with the help of a local technician. Figure 11 shows a sketch of different views of the QUARTIC prototype. Test beam results are discussed briefly in the next section.

We are constructing two new QUARTIC detectors with 12 and 15 mm long mini-bars and 10 $\mu$m pore tubes for a test beam run in March at Fermilab. The new box for housing the detectors was built at Fermilab and is shown in Fig. 12. We plan to instrument the middle two rows of each detector for the next run.
Figure 8: Three views of the initial QUARTIC time-of-flight Cerenkov counter, consisting of a 4x8 array of 6 mm$^2$ fused silica rods, coupled to a micro-channel plate PMT.
Figure 9: Simulated results showing the arrival time of photons at the MCP-PMT ($t=0$ corresponds to the arrival time of the first photon) for a mini-bar combined with an aluminized air light guide.

Figure 10: First GEANT simulation results showing: (left) the case where the detector is aluminized and all the light is reflected (right) the case of cladding, where some of the light escapes.
Figure 11: (a) A schematic side view of the QUARTIC box showing the position of the four mini-bars; (b) A schematic top view showing the four instrumented channels and the MCP-PMT; (c) A top view photograph showing the four mini-bars in the air light guide.

Figure 12: Photograph of updated QUARTIC detector prior to insertion of the mini-bars.
4.6.2 GASTOF

Our collaborators in Louvain have been evaluating an alternate PICO-TOF concept based on a gas Cerenkov counter. Gas Cerenkov detectors are very light and thin in terms of radiation lengths, hence can be used in the tracking systems for high energy charged particles, also in a highly irradiated environment. They often suffer from a limited number of Cerenkov photons, but can produce very narrow light pulses. Maximizing light output and minimizing the device length requires a gas with a relatively high refraction index (for a gas this means $n > 1.01$) like C4F10 or C4F8O.

A conceptual diagram of GASTOF is shown in Fig. 13. To minimize the amount of material traversed by measured particles and keep the MCP-PMT out of the beam, the Cerenkov light is reflected using a mirror. Figure 14 shows the distribution of arrival time of photons for a simulation of the first 30 cm long prototype using the C4F10 radiator. The width of the pulse is about 1 ps, and 13 photons are expected after collection and quantum efficiencies are taken into account. The sharpness of the timing is due to the geometry and radiator of the detector, which is arranged such that nearly the entire Cerenkov cone arrives at the same time. Also, since the speed of the proton and photon are comparable due to an index of refraction near one, light emitted at the beginning of the radiator will reach the PMT at a larger radius but similar time as light emitted close to the end of the radiator.

Two prototype detectors were constructed at Louvain; they each had a flat mirror with enhanced ultraviolet reflectivity and the Burle 25 µm pore MCP-PMT with a fused silica window. The results of laboratory tests were very promising [27], and were confirmed by test beam studies as discussed below. New prototypes are in preparation using the 6 µm pore Hamamatsu R3809U-50 MCP-PMT (generously donated by Hamamatsu), which according to specs has a single photon resolution less than 25 ps.

![GASTOF Diagram](image)

Figure 13: Schematic of GASTOF, a gas-based Cerenkov counter proposed by Louvain, as described in text.
The Fermilab Meson Test Beam Facility provides a beam of particles ranging from 5 to 120 GeV at moderate intensities (< 1 MHz) [28]. The PICO-TOF collaboration formed a test beam experiment, T958, with Brandt as spokesman to test both QUARTIC and GASTOF prototypes. Figure 15 shows the test beam setup for T958, which ran for several days between mid-August and mid-September 2006. Louvain contributed the GASTOF counters and some electronics, UTA provided the DAQ software, the fused silica bars, some electronics and most of the cables and connectors, while Alberta provided the air light guides, and Fermilab provided beam and NIM/CAMAC modules through the equipment pool. All of the groups contributed manpower to the effort.

Figure 16 shows the electronics associated with each channel (a NIM/CAMAC DAQ was used). For this test beam run both sets of detectors used the Burle 85011-501 25 µm MCP-PMT. We used specialized amplifiers with bandwidth on the 1 GHz level (Hamamatsu 5594 for the GASTOFs and ORTEC 9306 for two of the QUARTIC channels and a Louvain-made amplifier using the Phillips BGA2712 chip for the rest), combined with NIM four-channel 100 MHz ORTEC 934 CFD’s for all but two channels which used GHz ORTEC 9307. All channels were read out by the Phillips 7186 16 channel TDC, which has a 25 ps least-bit in highest resolution mode.

Although the first test beam run was primarily a learning experience as our first foray into fast timing, we did obtain results that were sufficiently encouraging to warrant further development. Figure 17 shows the difference in time between the two GASTOF counters for a test beam run at maximum tube voltage of 2500 V; the 94 ps difference corresponds to 67 ps/counter, an excellent result considering the electronics being used (the ORTEC 934 CFD alone is expected to have a 50 ps resolution). The typical single bar QUARTIC resolution was...
110 ps at 2300 V. The worse resolution was due to several factors: intrinsically worse resolution from the detector technology, non-optimization of the CFD, uncertainties in the height of the track in the bar, additional contributions from smaller photon statistics/bar, and lower gain from the lower voltage setting. We did, however, observe the expected $\sqrt{N}$ improvement in performance for events with several valid channels. The efficiency for GASTOF was greater than 90%, while the typical QUARTIC bar efficiency 50 to 60%, likely due to a lack of optimization of the CFD’s (one bar was 90% efficient). Preparations are underway for a second test beam run in March with new prototype detectors, improved electronics, and upgraded analysis software.

Figure 16: The electronics associated with each channel as described in text; a few different combinations of amplifiers and constant fraction discriminators (CFD) were used.
In addition to a fast detector and a fast MCP-PMT, the readout electronics also must be extremely fast with low noise to attain our 10 ps goal. We are fortunate to have experienced top-notch electrical engineers at Louvain (Luc Bonnet) and Alberta (Lars Holm) working on the project. Luc developed the fast amplifier board (using the Phillips BGA2712 chip) that we used in the test beam. Jerry Va'vra, the SLAC expert who is consulting on our project, tested the amplifier and found it to be almost as good as much more expensive commercial units.

The largest single contribution to the timing resolution in our last test beam run was the constant fraction discriminator, so for the March test beam run Luc has designed a CFD board, shown in Fig. 18(a). This is a very fast unit designed to work with rise times as short as 150 ps, and to be insensitive to the non-linearity and saturation of the amplifier. The board, currently undergoing tests, has been highly optimized for speed and is very compact. It will be possible to remotely control the threshold, an important feature for test beam.

The Alberta board shown in Fig. 18(b) provides an integrated amplifier and CFD and is expected to be available for the August test beam run. The amplifier uses the Phillips BGA2717 chip, while the CFD is based on the one developed by Alberta for the GlueX experiment. The circuit has been upgraded to use the most recent comparators and logic. The combination of amplifiers are such that the layout can use strip line connections between components. Every effort will be made to eliminate crosstalk and noise, especially the high frequency noise.

Initially we will use these boards in conjunction with the CAMAC Phillips 7186 25 ps TDC that we used in the first test beam run. Next we will try the CAEN 1290 VME board which uses the CERN developed HPTDC chip that also has a 25 ps least bit, but is radiation hard and has been designed for use at the LHC. The ALICE collaboration has attained better than 20 ps resolution in tests [29]. Further upgrades may involve combining this chip in an
integrated board, based on the outcome of the summer test beam. We are also exploring other TDC options in an attempt to get a 10 ps or better TDC performance. This may be possible due to the limited dynamic range of 1–2 ns required for the LHC application.

Figure 18: (a) Schematic of Louvain CFD board; (b) Schematic of Alberta amplifier/CFD integrated board.
7 Plan of Work

The University of Texas, Arlington is leading the project, performing simulations, and developing the QUARTIC counter. We are responsible for the data acquisition, interface with the Fermilab test beam, and will provide manpower for setup, data taking and analysis. The University of Alberta (Jim Pinfold and colleagues) are leading the effort to develop the electronics circuit and are also performing simulations. They will also participate in the test beam effort. University of Louvain (Krzysztof Piotrzkowski and colleagues) are developing the GASTOF detector and will provide a prototype for testing and an alternate set of electronics. Fermilab is building the new QUARTIC prototypes and providing test beam support.

We plan to continue to improve and test the PICO-TOF detectors until we reach the best resolution possible with this concept, ideally converging on a 10 ps resolution detector. Even if no further improvements were made beyond the results of the first beam test, a TOF measurement for FP420 (which now plans to use one GASTOF at the beginning of the spectrometer and two QUARTIC’s at the end) would give a better than 40 ps track measurement and a ten-fold rejection of background. We believe planned upgrades to the detector along with a dedicated CFD board being designed by Louvain will help us attain an overall resolution of 20–25 ps per track (40/60 ps for a single channel of GASTOF/QUARTIC respectively) in the March test beam run. In this run we will be in a better position to make advances due to the availability of automated data analysis software written by UTA graduate student Pedro Duarte to allow the quick feedback needed for systematic studies. Based on these results and comparison with simulations, we will optimize the detector parameters, such as orientation, thickness of bars, aluminization vs. air gap, etc. We will evaluate the different MCP-PMT tubes as well.

To attain the ultimate resolution of 10 ps for GASTOF and 30 ps for a QUARTIC bar (with 8 bars per track, that would imply a \( \sqrt{8} = 2.83 \) reduction factor giving about 10 ps for the detector), better measurement devices are needed to evaluate the results, motivating the purchase of a fast oscilloscope (Tektronix DPO70404) and a precision pulsed laser setup (PiLas EIG1000D control unit with PIL040 optical head). Both the SLAC and Nagoya groups noted that the systematic error of their timing circuit was a significant component of their overall timing resolution, consequently we feel it is critical to have a high resolution alternative to evaluate the different contributions to the resolution. For the Summer 2006 run we borrowed a 2.5 GHz bandwidth Tektronix DPO7524, which is a wonderful device, but we did not have access to it for long enough to take advantage of its capabilities. As part of this proposal, we plan to purchase the 4 GHz bandwidth Tektronix DPO70404. This PC-based scope has a jitter of about 0.9 ps, and will allow us to measure the time difference between pulses on the picosecond level. Although the sampling rate for a single channel is only 40 GS/s (Gigasamples/second) corresponding to a sample point every 25 ps (for two channels it is 20 GS/s or 50 ps), Tektronix claims that in interpolated sampling mode using their hardware \( \sin(x)/x \) interpolator, we can fill in intervening points down to 1 ps resolution. We will be able to operate the scope in remote mode allowing us to control it from a Windows PC outside the test beam area, and capture multiple events using the FastFrame feature. In addition, they will provide TDSJIT3 jitter analysis software to help analyze the sources of jitter in the circuit. They have offered us a deep discount of 43%, quoting us a price of $25,000 on their $44,000 DPO70404 oscilloscope.

The PiLas laser diode we have specified produces a sharp 408 nm pulse with a jitter of less than 3 ps and a repetition rate of up to 1 MHz making it ideal for evaluating our electronics. The combination of the laser diode with the oscilloscope will provide the critical information we need to attain this very challenging resolution level. We would proceed in the following way:

1. We can use the PiLas in single photon mode with the scope to measure the resolution of
each MCP-PMT allowing us to evaluate the transit time jitter of the different tubes.

2. We can tune the laser intensity to match the predicted detector response and see if we get the expected scaling with the square-root of the number of photons.

3. Using the laser, we can then study the effect of different amplifier/CFD combinations using the scope or the TDC for the timing measurement, allowing us to isolate the effect of each component on the resolution.

4. We can repeat the previous step for the test beam/detector input instead of the laser.

Identifying each component of the resolution allows us to focus on the component that is the largest contributor to the resolution, which will make the August/September test beam more useful and allow us to test the final design in early 2008. A 30 ps QUARTIC bar measurement given a TDC limit of about 20 ps would require 22 ps for the detector/PMT/CFD, which is very challenging but may well be attainable. A 10 ps GASTOF measurement cannot be done with current TDC’s, but given that only one channel is needed, Louvain plans to spare no expense. They propose to attain a 10 ps resolution by using a superior single channel tube (7 ps for their expected light output is conceivable) combined with an extremely expensive state-of-the-art single photon counter (5 ps) [30] that replaces the amplifier, CFD, and TDC.

**Milestones, with approximate dates:**

- March 2007: New test beam run planned for March 7–20 at Fermilab with improved detectors and the new Louvain Constant Fraction Discriminator board.
- April–June 2007: UTA will lead data analysis effort while Alberta and Louvain pursue development of integrated amplifier/CFD board. Simulations of detectors and electronics will continue.
- June 2007–August 2007: Purchase electronics components and Alberta boards. Purchase and setup oscilloscope and laser. Prepare for August test beam run at CERN.

**8 Summary**

**8.1 Project Goals**

We plan to simulate, build, and test two different types of designs for PICO-TOF, a new type of Cerenkov time-of-flight counter, with a goal of 10 ps time resolution. This includes testing not only the detectors, but also various micro-channel plate PMT’s, as well as different designs for the readout electronics. We will be in close contact with Burle and Hamamatsu with a secondary goal of giving them feedback to aid in improvements in MCP-PMT’s.
8.2 Evaluation Phase

We plan a series of test beam experiments to evaluate our progress, building on the initial test beam run in Summer 2006 at Fermilab. The tentative dates are March 2007 (prior to funding) at Fermilab, August 2007 at CERN, and February 2008 at Fermilab. We will also be using the PiLas laser diode system and Tektronix oscilloscope to study the tubes and electronics. The metric for this proposal is exceptionally clear: how close we can get to our 10 ps goal. Better than 20 ps would certainly classify the R&D as successful. As noted earlier, 10 ps per quartz bar is likely not attainable, but with eight bars, an individual bar measurement only has to be sub-30 ps. With a TDC limit of 20 ps or so this would require 22 ps for the detector/PMT/CFD which may be attainable. For the GASTOF detector, the single measurement places a higher performance burden, but also allows us to choose a solution that would be prohibitively expensive for a multi-channel system, namely a superior single channel tube with a state-of-the-art single photon counter.

8.3 Project Performance Sites

There will be multiple sites for this project. Electronics development and testing will take place at Alberta and Louvain, and then delivered to UTA for laser testing. Evaluation with beam will be performed at Fermilab and CERN.

8.4 Leverage

The entire effort for this project is being provided by UTA and collaborating institutions resulting in an enormous leveraging effect on DOE’s investment in the proposal. Electrical engineers are being provided by Louvain and Alberta, in addition to the senior personnel and/or students from the four collaborating institutions. Manpower and significant equipment is being provided by Louvain and UTA through local grants from Belgium and the Texas ARP program, respectively. Finally Burle and Hamamatsu have made significant in-kind contributions to the project by providing state-of-the-art photomultiplier tubes with a value comparable to the requested project funds.

8.5 Intellectual Merit

The intellectual merit of this proposal is noteworthy as it will not only lead to a newly designed and tested detector that is pushing the envelope of fast timing, but also due to the numerous physics applications of this detector. While we have focussed on the discovery physics, such as the Higgs boson, there will be many other physics topics at the LHC that will benefit from viable proton detectors. Improved micro-channel plate detectors can be used in other areas of particle physics, for example the study of CP violation, through large area TOF’s. Finally, the impact of helping to improve the MCP-PMT’s will not only be felt in particle physics, but also in diverse areas such as condensed matter physics and medical imaging.
9 BIBLIOGRAPHY


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