Advanced Detector Research Electronics for a Picosecond Time-of-Flight Measurement

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1 Introduction and Motivation

Time-of-flight (TOF) detectors have historically been used as part of the particle identification capability of multi-purpose particle physics detectors. Such detectors (for example, the Run II CDF TOF detector [1]) typically measure the flight time with a resolution of about 100 ps, which, when combined with a momentum measurement in a magnetic field, is sufficient to determine the particle’s mass, and thus its identity. Recently, time-of-flight detectors employing Cerenkov radiators read out by micro-channel plate photomultiplier tubes (MCP-PMT’s) have made it possible to achieve time resolutions on the 10 ps scale (see, for example, the ground-breaking work of the Nagoya group [2]). 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 exceeds the local speed of light in a medium.

The ability to accurately measure the flight time depends on three key elements: the radiator, the photo-sensor, and the electronics. Detectors capable of a 10 ps measurement have typically been readout by oscilloscopes or single photon counters, which are not practical solutions for a multi-channel system, or a detector in a high radiation area.

The fast timing sub-group of the FP420 R&D collaboration [3] has been pursuing an alternate approach, making multiple measurements on the 30 ps level. Multiple measurements of the same particle (such as in the detector described below) has several benefits: it eliminates background from thermal noise, which is particularly important for SiPMs, where the dark noise can be on the MHz scale; it provides redundancy (increased efficiency); and most importantly it significantly improves the timing resolution: e.g. naively, eight independent measurements of 28 ps precision average to a single 10 ps measurement. The readout electronics in this scheme need to have a resolution on the 20 ps level, which is a much more modest and obtainable goal, and is the focus of this proposal.

Supported by funding from the 2006 ARP program [4] and 2007 DOE ADR grant [5], University of Texas, Arlington (UTA) Professor Andrew Brandt has been leading the development of the "QUARTIC," (Quartz TIming Counter) detector based on these concepts. Figure 1(a) shows the basic design: a proton passing through a series of fused silica bars radiating photons which are measured by an MCP-PMT. Each proton passes through all eight $z$ segments for a given $x$, providing eight separate time measurements along the track (the inset shows the $4 \times 8$ array of bars with a $5 \text{ mm} \times 5 \text{ mm}$ cross section and an average length of about 10 cm).

UTA, Alberta, and Stony Brook have taken up the challenge of developing the full chain of readout electronics necessary to make optimal use of this detector. Figure 1(b) shows the time difference of two non-adjacent quartz bars through the full readout chain from a test beam run at Fermilab in November 2010: the 48 ps resolution implies an individual bar resolution of 34 ps, of which about 27 ps is estimated to be due to the radiator/PMT with about 20 ps due to the electronics.

In this proposal we first outline a physics use case for this type of fast timing detector electronics, and then in the following sections discuss the details of the electronics system, followed by the programs of work for UTA and Stony Brook.

2 Physics Motivation

Diffractive physics, in which one or both beam particles remain intact in a high energy collision, has been used primarily as a tool for understanding the theory of strong interactions QCD. In Ref. [3], we have proposed to use diffraction as a means of searching for new physics beyond the Standard Model [6] using the so-called “central exclusive production” (CED) process. In central exclusive production (recently observed by the CDF and DØ collaboration at Fermilab [7]), the
incoming protons are scattered at small angles and the entire momentum lost by the protons goes into the creation of a central system. This process provides a particularly clean environment to search for and characterize new particles at the CERN LHC in Switzerland, which will ultimately have seven times the beam energy of the Fermilab accelerator. A notable example is the exclusive production of the Higgs Boson, a critical, yet undiscovered, component of the Standard Model. If the outgoing protons remain intact then the centrally produced Higgs is created in a spin zero, CP (charge parity) even state, thus the observation of this process determines the quantum numbers of the Higgs (or any other observed resonance).

Apart from the QCD-based CED process, photons can be exchanged in an analogous QED process. This process is calculable to a high level of precision and its measurement is thus extremely sensitive to anomalous couplings between photons and weak vector bosons [8].

Furthermore, the proton momentum measurement results in a mass resolution of about 3 GeV per event, much more precise than direct measurements using the central ATLAS detector. This is an especially promising approach for many “Beyond the Standard Model” scenarios, where the cross section for a Higgs coupling to $b$ quarks is enhanced at the expense of vector bosons, making the proton tagging method the only approach for measuring the Higgs quantum numbers prior to the construction of a multi-billion dollar linear collider (See Refs. [3] and references therein). The excellent mass resolution achievable with suitable proton detectors, combined with background suppression from quantum number selection rules, gives a viable signal and signal to background ratio for these models. Tagging the protons allows the LHC to be used as a tunable center-of-mass energy gluon-gluon or photon-photon collider, opening a wide range of new physics possibilities.

Forward detectors at 220 m and 420 m have been proposed for the two large LHC detectors ATLAS and CMS, and Letters of Intent have been approved by both collaborations, which are in the process of preparing Technical Proposals (TP). A 10 ps time measurement from timing detectors on either side of the interaction point would provide a 2.1 mm vertex resolution, which, when combined with the excellent 50 $\mu$m vertex resolution of the central system would provide a large rejection of the dominant combinatoric background from multiple proton-proton interactions in the same bunch crossing. This ADR supports R&D for the novel ultra-high-resolution timing electronics necessary for a TP. Without an approved TP, the Forward Physics program cannot be a recognized part of physics upgrade program of either collaboration.

### 3 Scope of this ADR proposal

Several types of Cerenkov photon detectors are currently available that deliver the required timing resolution including MCP-PMT’s and avalanche photo-diode arrays, also known as Silicon photo-
multipliers (SiPM). These detectors all feature rise times of 100 to 400 ps and transit time jitter of better than 30 ps when combined with a radiator that produces \( O(10) \) detected photoelectrons (like the QUARTIC detector described above). In this ADR we do not address the radiators or photo-detectors, but concentrate on the electronics. We describe a plan to develop and study the full electronics chain for a time-of-flight particle detector with an extremely precise resolution of 20 ps/channel.

For a typical detector the photo statistics are limited. Thus, the signal amplitude fluctuates significantly from event to event resulting in large amplitude-dependent time shifts (time-walk) if a simple fixed threshold discriminator is used, precluding accurate timing. Consequently, there are two basic options given a detector with limited photo statistics: 1) employ a constant-fraction discriminator (CFD) followed by a time to digital converter (TDC); 2) determine the time by sampling, storing, and analyzing the full signal shape.

We have chosen the former approach, and have successfully tested the following electronics chain: preamplifier (two mini-circuits ZX60-4016E amplifiers in series separated by a 6 dB attenuator, providing a factor of 50 multiplication), CFD (Alberta has made a custom NIM unit with a mother board that provides filtered power, and houses 8 single channel CFD’s, based on an initial design of Louvain), TDC (Alberta made a TDC board incorporating the CERN/CAEN designed HPTDC chip that deals with all the buffering and control signals necessary for interfacing with ATLAS readout). While this chain has proven effective, it is not sufficient.

The desired system includes the following:

- Eight timing channels in parallel to minimize time dispersion and to allow for multiple measurements of the same particle for noise elimination and further improvement of resolution.
- An 8-channel pre-amplification board, with 5 m pig tails to bring the signals from the detector to a low-radiation area.
- A high resolution 8-channel CFD
- A fast programmable or hardwired majority/coincidence trigger output of a set of 8 channels, available within about 50 ns of the particle’s arrival.
- A Low resolution 8-bit digital pulse height information accompanying the timing information. This information can be used to eliminate pathological events, to monitor of the gain stability of the photosensor, and to correct for any residual time walk.
- An ultra-stable reference clock to be used as “start” signal and to precisely synchronize several time-of-flight detectors together with better than 5 ps accuracy. This ”start” time can digitized in parallel with the arrival times.
- A high precision TDC.

We have searched for systems with these capabilities available on the market or under development, but without success. Fast analog memory approaches that use the stored waveform to determine precise timing \[9\] are quite promising for certain applications, but generally have at least one, and typically several, of these undesirable features: limited repetition rate, insufficient time resolution, too large data size, not radiation tolerant, or unable to provide a fast trigger.

In this ADR we propose to develop all the components of a full electronics readout system with an intrinsic time resolution of 20 ps per channel or better. We plan to develop the electronics as a series of “building block” that can be used as is, or can be individually adapted to a particular
application. Indeed, we have already gone some way in this direction in a series of designs and beam tests of the QUARTIC detector for our use case, the LHC Forward Physics program. This has led to the development by Alberta of high resolution CFD and TDC components which we will use as starting point for the R&D described in this proposal. We note that for the LHC upgrades, the on-detector electronics will see radiation levels of about $10^{12}$ neutron-equivalent per cm$^2$, so we plan to evaluate the radiation tolerance of all the components, and determine the optimal geographical layout of the different elements. Other experiments such as Panda, LHCb, and Super B factories can all profit from some or all of this development work.

4 Work by the University of Texas at Arlington

In this section work by the University of Texas at Arlington (UTA) group is discussed. UTA has been leading the development of the QUARTIC detector, and the full time-of-flight system, including joint efforts with Photonis and Photek to improve the MCP-PMT lifetime. UTA has developed significant fast timing expertise through the establishment and operation of the Picosecond Test Facility. This facility contains a Hamamatsu PLP-10 pulsed picosecond laser, various optical and RF components, fast electronics, and a 6 GHz LeCroy WaveMaster 8620a oscilloscope. It is manned primarily by physics undergraduate students under the supervision of Prof. Brandt with the assistance of graduate students Ian Howley (3rd year) and Ryan Hall (worked on the project for two years as an undergraduate and now in first year as a graduate student). Research Assistant Professor Seongtae Park has also contributed to the operation of this facility. In addition to overall project leadership, the main activities of UTA will be to develop a reference clock with a jitter of 1 to 2 ps, and to perform system tests of the full electronics chain, before, during, and after exposure of the various components to radiation.

4.1 Reference Clock

A crucial component of the time-of-flight system is the reference clock, used to tie together measurements 100’s of meters apart. The proton use case requires the time difference between protons detected up to several hundred upstream and downstream of the central detectors. Practically, this is done by taking the time difference with respect to a stabilized clock signal. For the clock signal to cancel in the time difference it must have a low jitter of 5 ps or less, or it would not be negligible relative to the proton time resolution. The reference timing stabilization circuit is based on a design developed at the Stanford Linear Accelerator Center (SLAC) by Joe Frisch and Jeff Gronberg (LLNL), who is a consultant on this project. It uses a phase locked loop feedback mechanism as shown in Fig. 2(a). A voltage controlled oscillator (VCO) launches a signal down the cable from the tunnel near the proton detector to the interaction point (IP), where it is reflected and sent back. At the IP end of the cable the signal is sampled with a directional coupler where it is compared in the mixer with the 400 MHz Master Reference, provided in this example from the LHC RF signal. The result is a DC voltage level that is fed back to the VCO to maintain synchronization. Changes in the cable’s electrical length cancel when the original and returned signal are added. A high quality large diameter air core coaxial cable was used with a 476 MHz RF signal for preliminary tests, and the stabilization circuit yielded a 150 fs jitter over a 100 m cable. Figure 2(b) shows results from a second test, with a 300 m cable, which was left outside to verify the temperature stability of the circuit. A low noise amplifier was used to boost the return signal to recover the cable and power coupling loss, which are a function of cable length (the measured attenuation was about 7.5 dB for the 300 m cable). The unstabilized circuit was observed to have a variation of 80 ps/10 degrees C, while the stabilized circuit (shown in the figure) reduced the variation to 4 ps/10 degrees C. A residual correction as a function of temperature could reduce this drift to the 1 to 2 ps level, but we propose to control the temperature of the electronics, which is likely the cause of
the residual variation. This should bring the drift to the sub-picosecond level along with the jitter. This temperature stabilization is important for us since the seasonal variation in the LHC tunnel is about ±10 degrees C.

The output of the SLAC circuit is a stabilized 476 MHz RF wave, but we require a 40 MHz square wave pulse from the 400 MHz LHC RF. This will be an input to the trigger board, which will pass the clock through to the HPTDC board for triggered events. The circuit will be developed by a UTA electrical engineering (EE) graduate student under the supervision of UTA EE Professor’s Alan Davis and Ron Carter, both of whom have extensive RF experience. Initial ideas for accomplishing this include a programmable logic chip or an ECL divider chip. The design and fabrication of the reference timing circuit and the interface to the HPTDC board is a significant area of development for this proposal, and will also require modifications of the initial SLAC circuit to ensure that the expected location of the various components are consistent with expected radiation levels in the LHC tunnel.

Figure 2: (a) Schematic of the Reference timing system as described in text. (b) Results of temperature stabilization test showing a mild drift with temperature (about 4 ps for 10 degrees C).

5 Work by Stony Brook University

In this section we describe work to be performed by Stony Brook in the ADR proposal. The Stony Brook personnel on this ADR proposal are Rijssenbeek, Schamberger, and technician Steffens.

The full timing electronics chain is shown schematically in Fig. 3. In the following sections, we describe each building block in some detail: its R&D plan, and its estimated cost. The budget proposal for Stony Brook follows the project description.

5.1 Preamplification

In the laboratory and in beam tests, we have successfully used the ZX60 series 4 GHz bandwidth, 20 dB gain coaxial amplifiers from Minicircuits[10], with low noise figures and good stability and reliability. This single-channel preamp is fully shielded and has SMA I/O connectors. Thus, it is bulky and has high cost $50/piece.

Minicircuits also offers the 4 GHz-bandwidth 14-20 dB gain ERA-5+ monolithic Darlington amplifier in a micro-X package ($3.85/pc, 1-30 pc), which appears well suited to our needs. Together with various passive SMT components, shielding and cables, this amplifier will cost about $20/channel in R&D quantities. We plan to design and build a double layer (signal and ground) PCB layout for this part, with a small 0.2” × 1.2” footprint per channel, in an eight-channel version.
Figure 3: The electronics chain used for QUARTIC in test setups: the low-noise 3 GHz bandwidth preamp ZX60 (by Minicircuits), followed by the Louvain constant fraction discriminator, followed by the Alberta HPTDC.

Other suitable amplifiers (Agilent, Minicircuits) may be tested as well.

As we require radiation tolerance, we propose to expose this device under power and pulsed electronically to beam and radiation. Several test beams, at FNAL and CERN, are available to us for this purpose, where we can participate parasitically. In conjunction with UTA, we will characterize the device just before, during, and directly after several irradiation periods, while monitoring the dose rate and total accumulated dose. We plan to use a fast programmable pulser and a high bandwidth digital scope to complement UTA laser tests in performing this characterization.

In year one, we propose the construction of two 8-channel shielded preamp boards equipped with nine 5 m long RG316U-DS[11] coax SMA pigtails (8 signals and 1 power), with a PCB size of about 2.0” × 1.5”. We will study the effect of radiation dose and of the coax signal cable runs on the signal shape and timing resolution and jitter.

The cost of an 8-channel device is estimated at $400 not including the labor, which is supplied by our university-supported technician. For year 1, we budget $800 for two preamp boards, and $3,000 for beam test (supplies: jigs, cables, etc.). For year 2, we budget $800 for the construction of two final-version preamp boards.

5.2 Constant Fraction Discriminator and Trigger

We chose a constant-fraction discrimination to provide a precise timing logical pulse. This is a well-established technique, and we have an excellent baseline device in the existing Alberta-Louvain Constant Fraction Discriminator (ALCFD), which we have used before in beam tests. An 8-channel NIM module with a RS232 interface for control has been built by Alberta and has a measured timing resolution of about 5 ps.

Although this module provides proof-of-existence, much further R&D is required.

First, a 10× receiver/amplifier is required at the input, possibly with programmable gain for
optimal adaptation to the CFD section. The CFD can be further optimized based on operational experience obtained with ALCFD prototypes.

Second, we must develop a motherboard – possibly in VME format – for an 8-channel system, and design and implement programmable trigger Majority-AND logic to form a coincidence. We plan to route the fast timing signals to the motherboard which implements the fast trigger circuitry.

Second, we propose to incorporate a sample-and-hold amplifier inside each CFD channel. These slow analog signals are made available on the front panel for optional digitization by fast low-resolution flash ADCs, located in the Time and Analog Digitizer module (TAD), if the trigger condition is satisfied.

The precision reference clock – the “start” signal – may also be part of the trigger condition, and will be routed to a separate (ninth) input on each CFD module. All fast timing signals (including the clock), if satisfying the trigger condition, are transmitted (via either an analog backplane or coax cabled) to time digitizer modules.

We aim to develop a CFD module with an inherent time resolution of 7 ps/channel or better. The trigger logic must respect this resolution limit as well. Together with the S/H circuit, this is the main R&D task for the CFD in this proposal.

Based on Alberta experience, we estimate the cost for the CFD and Trigger R&D as $2,000 per 8-channel CFD module. In year 1, we propose to purchase two of these modules for testing and R&D from Alberta for $7,000 total. Also in year 1, we will do R&D on implementing a preamplification step at the CFD input ($400), adding a suitable S/H amplifier for fast low-resolution pulse height measurement ($3,000), and adding trigger capability ($1,000) to the motherboard.

In year 2, we propose to build two final version CFD modules based on the year 1 results. Including materials and supplies (unforeseen costs, and cables and connectors), we budget $8,000 for final-version CFD and Trigger.

5.3 Time and Analog Digitizers

From the CFD, the digital timing signals enter the High Precision Time-to-Digital Converter (HPTDC) board. An early 4-channel version of this module was developed by Alberta using the high resolution 8-channel HPTDC chip developed by CERN for Time-of-Flight detectors. In the lab we have obtained a 14 ps/channel resolution, close to our design goals. HPTDC chip development is continuing at CERN and more powerful versions may be used in future editions of the HPTDC module.

Several items need significant development beyond this proof-of-existence prototype.

At high event rates the occupancy of the current HPTDC chip grows, causing loss of data: in 8 channel high-resolution mode (25 ps LSB), the HPTDC chip is limited to a maximum occupancy of about 2 MHz. Simulations show that by doubling the internal clock speed to 80 MHz and using only four channels per chip, the occupancy limit can be increased to 16 MHz at less than 0.1% losses. This capability is satisfactory for our LHC application (expected maximum 10 MHz trigger rate), but is unacceptable for the 40 MHz reference timing signal at the LHC; hence it too is filtered by the trigger.

In addition, we aim to provide a fast, low-resolution pulse-height determination for pulses that pass the trigger in order, for instance, to allow residual time-walk corrections off-line. Hence we aim to design 8-bit, 50 ns ADC circuitry (using video digitizers) which can either be implemented as a stand-alone 8-channel module, or incorporated into the HPTDC module. This ADC circuitry is the main R&D task for this digitization stage.

The interface to the data acquisition will be made configurable, so that it can be adapted to specific experimental requirements.

In year 1, we purchase two 8-channel HPTDC modules at $3,000 each from Alberta (price quote
included). These will be used in tests and as basis for design of a final version that has high rate capability and possibly includes the ADC functionality. In year 2, we budget for two final-version modules at $4,000 each.

5.4 Infrastructure

For this R&D proposal, we require a fast programmable pulser (e.g. the TEK AWG5012 2 Channel, Arbitrary Waveform Generator) and fast 6 GHz bandwidth, 20 GS/s digital scope. We propose to purchase a refurbished AWG5012 for $27,883, see the included price quote.

The required fast digital scope is available to us in our departmental electronics shop. Our group has exclusive access to a mostly university-paid, grant subsidized, senior electronic and mechanical technician. We have a well-instrumented electronics lab as well as cheap access to the department’s electronics shop. We have a strong record in developing and building fast electronics systems for experiments: The DØ calorimeter electronics, the DØ Silicon track trigger, and read-out for the PHENIX Silicon vertex detector.

5.5 Stony Brook Budget

In this ADR we budget only costs of parts purchased and the fabrication of PCB, cables, etc. produced by outside vendors. Labor is supplied by our senior university-supported technician, possibly with additional aid from undergraduate students on Stony Brook URECA grants.

The budgeted Arbitrary Waveform Generator is equipment and free of overhead. The indirect cost percentage for this proposal is the same as our standard ATLAS grant: 33.75%.

6 Bibliography

References


[11] RD316 Flexible Double Shielded 0.114” 50 FEP SPCW Stranded 0.0201 PTFE M17/152-00001 RD316 12.4 GHz 19.00 27.00 43.00. Price (Pasternack.com): RG316U-DS $1.82/ft (50-99ft)