Fast Timing Detectors for High-Rate Environments

Proposal to XXX

for R&D in Association with

Solicitation DE-FOA-0000407

DoE Office of Science Detector R&D Program

(Period of Performance July 1, 2011 - June 30, 2012)

1 Introduction

The physics reach of forward detectors at hadron and lepton colliders would be greatly enhanced by precision timing with resolution $\approx$ 10 psec, so as to tag the primary interaction vertex to within 3 mm by the timing of forward-proton pairs, but the detector must survive in environments with very high fluxes of particles. High-performance avalanche photodiodes (APDs) offer the prospect of both precision timing in a detector of simple geometry and relatively long lifetime in a harsh environment. Preliminary evaluation of one such sensor,[1] with a beta source is encouraging that a concerted effort be made now to characterize the limitations of large-area APDs for precision timing, due to transit-time spread when subject to charged particles over their entire active area. Square detectors of various areas, with a single readout electrode and also with readout at the four corners, will be tested in the recently developed (by us) single-electron test facility with picosecond timing at the BNL Accelerator Test Facility. Some of these detectors will be irradiated by 200-MeV protons to study the rise in leakage current with dose, and to check for damage by occasional unusually high proton-induced ionization (nuclear counter effect).

For this effort we request funds of $\approx$ \$33.4k for a one-year study (in collaboration with physicists from Princeton U, who are submitting a parallel proposal for \$49k).

2 Scope of Work

2.1 The Physics Opportunity for Ultra-Fast Timing at the LHC

The principal physics motivation for the present proposal is the needed for precision timing on forward-backward (small angle) pairs of protons at the LHC, such that the interaction vertex, and corresponding data in the central detector that contains many such interactions per beam crossing, can be correlated with a trigger on the forward protons. Of particular

[1] S. White *et al.*, *Design of a 10 picosecond Time of Flight Detector using Avalanche Photodiodes* (Jan. 16, 2009), http://arxiv.org/abs/0901.2530

interest is a class of Higgs boson searches, based on so-called central exclusive production, in which the Higgs decays to $b\bar{b}$ jets, $pp \to ppH$ with $H \to b_{\rm jet}\bar{b}_{\rm jet}$.[2] For this it is desired to locate the interaction vertex along the beam direction to within 2 mm using time-of-flight measurements on the forward protons (detected some 200-400 m from the interaction region). This sets the goal of precision timing to 10 psec, in a high-rate environment of hadrons, as stated in the context of the FP40 R&D project for forward physics at the LHC.[3]

2.2 Technical Challenges for Ultra-Fast Timing

Timing of 10-ps precision for high-energy particles has so far only been demonstrated with a multichannel plate photomultiplier (MCP-PMT).[4] Issues of MCP-PMT lifetime in a high-rate environment, and the difficulty devising a Čerenkov radiator to couple to the MCP-PMT with sufficient photostatistics and low transit-time spread, encourage us to investigate alternative technologies.

An appealing alternative, the subject of the present proposal, is the use of avalanche photodiodes (APDs). The planar silicon devices respond to charged particles (as well as to photons, their signal source in more typical applications), so they can be used without the radiator required with MCP-PMTs. This permits use of an array of APDs perpendicular to the particles' direction, as sketched in Fig. 1.

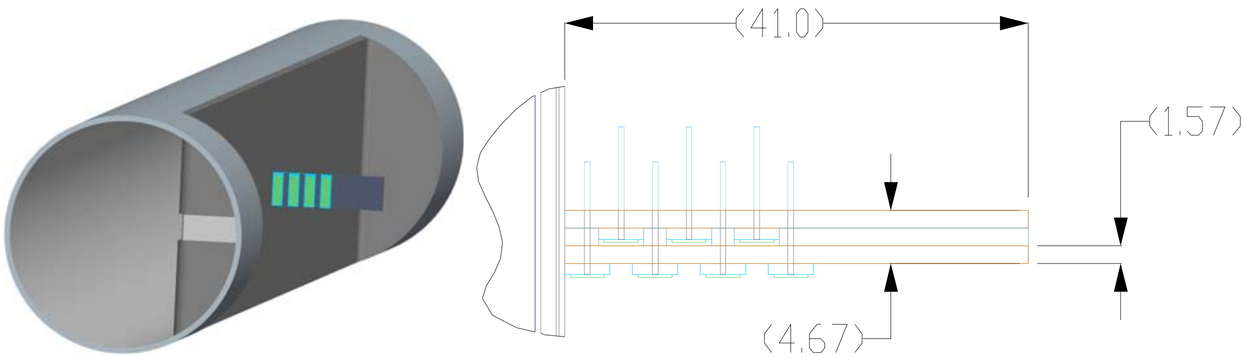

Figure 1: Left: Sketch of a possible array of 7 APDs in two layers outside a so-called Hamburg pipe. Right: Top view of the array of 7 APDs. From [1].

As with MCP-PMTs, the gain region of APDs is in a layer less than 1 mm thick, so that transit-time spread in the gain avalanche is only a few picoseconds. And, as is also the case with MCP-PMTs, the largest contribution to the transit-time spread is due to the path length variation between the position of the avalanche and the anode of the detector. In principle, this contribution to the transit-time spread can be minimized if the location of the charged particle over the surface of the APD is determined by an external tracking

[2] See, for example, B. Cox, *Detecting Higgs bosons in the $b\bar{b}$ decay channel using forward proton tagging at the LHC*, JHEP 2007, 10, 090, http://arxiv.org/abs/0709.3035

[3] M. Albrow *et al.*, *The FP420 R&D project: Higgs and New Physics with forward protons at the LHC.* JINST **4**, T1001 (2009), http://arxiv.org/abs/0806.0302

[4] K. Inami *et al.*, *A 5 ps TOF-counter with an MCP-PMT*, Nucl. Instr. and Meth. A **560**, 303 (2006).

device.[5] This will be verified as part of the proposed studies. In addition, we propose to determine the largest size of an APD that permits timing resolutions of 10 ps without use of an external tracking device.

Prototype square APDs with readout electrodes at all four corners are now available,[6] which should permit better timing resolution than with an APD of the same area by only a single readout electrode.

Three studies of the effect of transit-time spread on the time resolution of square APDs are the main focus of the present proposal:

- Time resolution of APDs with known position of the charged particles.
- Time resolution APDs in case of uniform distribution of the charged particles.
- Time resolutions of APDs with readout at all four corners.

Another key issue for use of APDs at a hadron collider is their lifetime against various forms of radiation damage. Bulk damage by passing particles leads to a rise in the leakage current, fluctuations in which eventually mask the signal pulses from the particles. Cooled operation of the APDs, and occasional annealing to 100° C should permit useful lifetimes of the APDs in excess of 1 year at the LHC, where forward fluxes of charged particles are expected to be about 10 MHz/cm^2 at luminosity of 10^{34} cm^{-2}s^{-1}.[7] The relatively low cost of the APDS make it affordable to replace them every year or two.

A separate issue is possible catastrophic failure of the APDs due internal discharges induced by heavily ionizing nuclear fragments (nuclear counter effect).[8] This issue is mitigated by careful design and processing of the APDs, but any particular APD fabrication should be checked for vulnerability to this form of damage. After the timing studies have been performed on the APDs that we plan to purchase, they will be irradiated, with a fraction of them under bias, at one several possible irradiation facilities (most likely at the Mass General Hospital 200 MeV accelerator). Should this form of damage be encountered, the response would be to investigate better design of the APDs, which is beyond the scope of the present proposal, but could form the basis of a continuation.

2.3 The APDs

The APDs that we propose to purchase for studies of time resolution *vs.* sensor size are from Radiation Monitoring Devices.[6]

[5]Test of an 8-mm-diameter hybrid avalanche photodiode (HAPD = APD + photocathode) showed 23-ps resolution for uniform illumination of the photocathode, whereas resolution better than 10 ps is inferred for point illumination. A. Fukasawa *et al.*, *High Speed HPD for Photon Counting*, IEEE Nucl. Sci. Symp. **1**, 43 (2006). An APD will have lower transit-time spread than an HAPD because the latter includes a several-mm-long path of the photoelectrons in vacuum.

[6]Radiation Monitoring Devices, Watertown, MA, www.rmdinc.com

[7]This inference is based on studies such at that of R. Grazioso *et al.*, *Radiation Hardness of High Gain Avalanche Photodiodes*, IEEE Nucl. Sci. Symp. **1**, 240 (2001).

[8]See, for example, G. Anzivino *et al.*, *Failure modes of large surface avalanche photo diodes in high-energy physics environments*, Nucl. Instr. and Meth. A **430**, 100 (1999).

1. A1604, a 4×4 array of pixels each 2×2 mm^2. Tests using a single pixel of this device will determine the minimal timing resolution of the APDs, even with external tracking of the charged particle. Then, this device can also be readout by electrically joining the anode pins of various groups of pixels, such as 2×2, 3×3 and 4×4, *etc.*

2. S0814, an 8×8 mm^2 area with a single anode pin. Tests with this can confirm the results of the study of time resolution *vs.* total active area by grouping the small pixels of the A1604 APD.

3. S1315, an 13×13 mm^2 area with a single anode pin. Tests with this device will extend the range of areas of the study of transit-time spread *vs.* area.

4. Prototype APDs of areas 8×8 and 13×13 mm^2 and readout at all four corners. Tests with these devices will demonstrate the improvement in timing resolution available when using "charge-sharing" readout which effectively localizes the charged particle.

In addition, we propose to purchase two 10×10 mm^2 APDs from Perkin Elmer[9] as an alternative to the RMB APDs, in case the latter prove to be more vulnerable to radiation damage by protons.

2.4 The Readout

We will perform timing tests with two different readouts of the APDs.

1. A Tektronix MSO70804 oscilloscope, 8-GHz bandwidth, 25 GSample/s. Use of this scope at the BNL Accelerator Test Facility (see following section) demonstrate that the timing of the electron beam observed in a stripline detector was about 2.5 ps (rms), as shown in Fig. 2.

2. DRS4 4-channel, 6 GSample/s, 750-MHz bandwidth digitizer (USB readout). As a potential lower-cost readout system for an array of APDs, we propose to explore their timing performance when read out with the DRS4 chip developed at Paul Scherrer Institute.[10] A preliminary evaluation of the timing jitter of a "loaner" board indicated that a time resolution of 10 ps (rms) can be achieved with these boards under ideal conditions.[11] We propose to make timing tests of the APDS with both the Tektronix scope and the DRS4 boards to verifying the effect of the latter on the time resolution of the APDs.

2.5 The Test Beam

The key tests of the present proposal will be performed in an electron beam at the BNL Accelerator Test Facility, in which single electrons are scattered out of a ps-time-scale pulse

[9] http://www.perkinelmer.com/Category/Category/KeyName/IND_DEF_CAT_AvalanchePhotodiodesAPD_004

[10] DRS Chip Home page, http://drs.web.psi.ch/

[11] M. Chiu etal, *Electronics Feasibility Study Using Waveform Digitizers for a 10 ps Time-of-Flight Detector* (Sept. 15, 2010), http://puhep1.princeton.edu/~mcdonald/LHC/White/chiu_091510.pdf

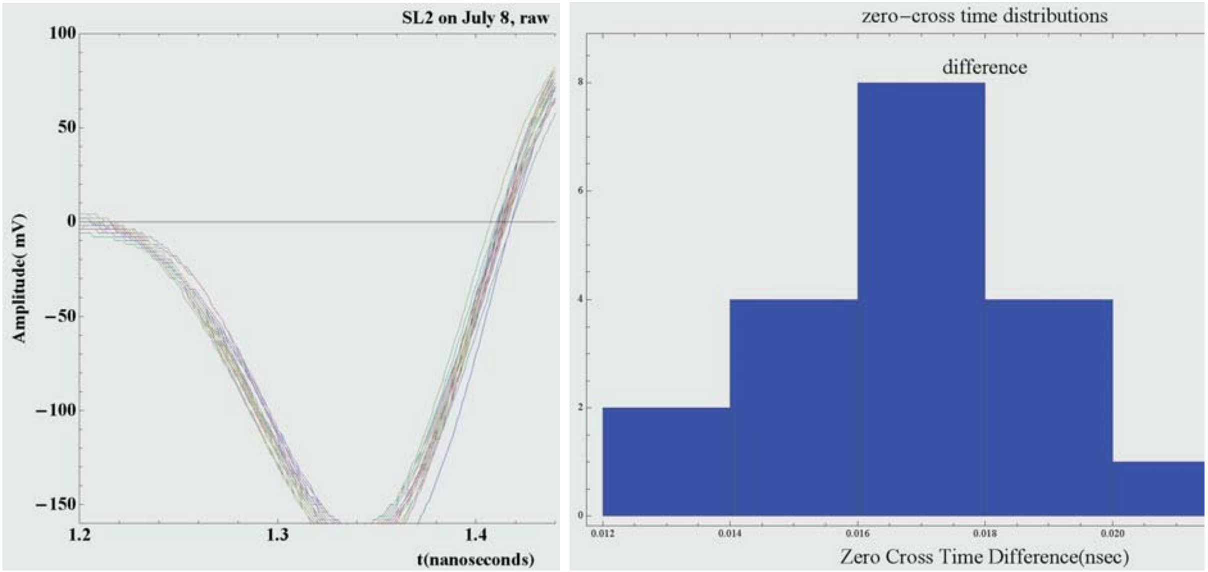

Figure 2: Left: Scope traces of signals from the electron beam of the BNL ATF. Right: Histogram of the zero crossing of the signals, with 2.5 ps (rms). Data collected July 8, 2010, by the BNL collaborators on the present proposal.

of $\approx 10^9$ electrons of 80 MeV energy by a Be foil. This secondary beam has recently been developed by our BNL collaborators, and a parallel proposal for use of this beam for tests such as those in the present proposal has been submitted to the AFT.[12] A schematic of this test beam is shown in Fig. 3.

2.6 The Test Plan

The RMD APDs and DRS4 readout boards are to be purchased by Princeton U. The Perkin Elmer APDs are to be purchased by BNL. Princeton will mount the detectors and prepare the connections for ganging anode pins of the A1604 APDs. BNL will provide the 8-GHz scope and the test beam. Together we will test the APDs in the test beam. Once set up, a run of only a few minutes suffices for a test of a particular configuration. A total of ten days of beam time has been requested, which is more than ample for the proposed suite of tests.

After the beam tests are complete, the APDs will be irradiated at an external facility, such as a 200-MeV proton machine at Mass General Hospital (favored), the CERN PS irradiation facility, the BNL BLIP facility, or a reactor at MIT. Irradiations up to 10^{14} protons (or neutrons)/cm^2 will be performed on pairs of APDs, one powered and one not, to explore both the issues of slow rise in bulk leakage current and abrupt failure due to unusually high ionization. BNL will take the lead role in irradiation and damage studies.

[12] M. Chiu etal, *Fast-Timing R&D addressing High-Rate-Capable Technologies using a Single-Electron, 3-Picosecond Beam* (Dec. 3, 2010, submitted to the BNL ATF), http://puhep1.princeton.edu/~mcdonald/LHC/White/ATF_proposal_final_k.pdf

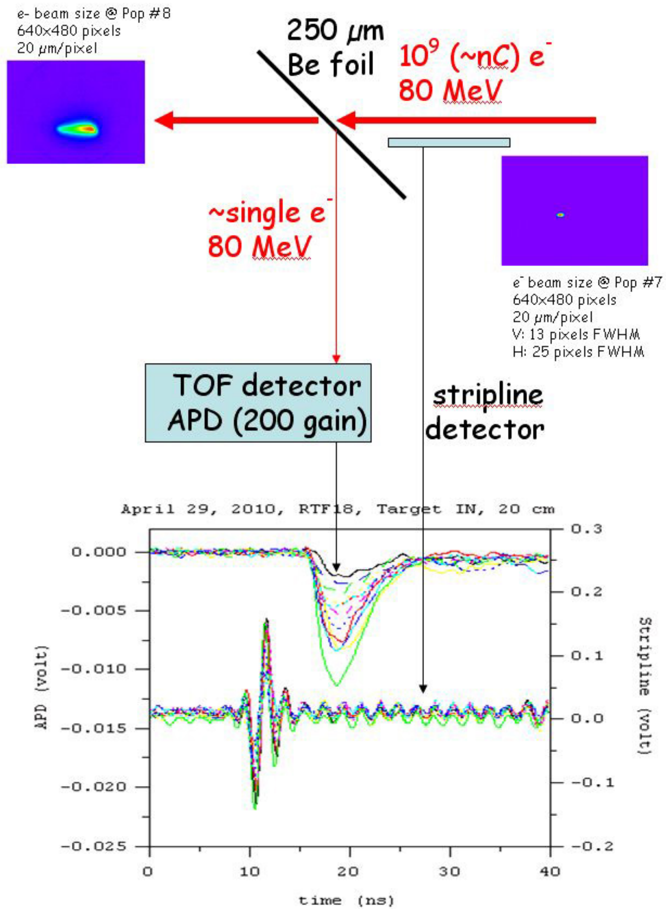

Figure 3: Schematic of the 80-MeV, single-electron test beam at the BNL Accelerator Test Facility. Single electrons are scattered by 90° by a Be foil. A fast-timing trigger is provided by the stripline monitor of the pulse of 10^9 electrons in the primary beam. From [11].

3 Budgets

3.1 BNL

Indirect costs (and fringe benefits on labor) as charged by BNL are included in the (approximate) numbers given below.

1. Materials and Supplies $16.2k
   (a) 2 APDs from Perkin Elmer $3.8k
   (b) Materials for radiation damage tests $2.7k
   (c) 8 Hours beam time at Mass General $9.7k

2. Effort $6.6k

   (a) Engineer(TBN) to design radiation damage tests $3.9k
   (b) BNL shop labor $2.7k

3. Travel $10.6k

4. **Total $33.4**

3.2 Princeton U

Funds for Princeton U are being requested in a separate proposal, and are lister here for reference only. Indirect costs (and fringe benefits on labor) as charged by Princeton University are included in the (approximate) numbers given below.

1. Materials and Supplies $38.6k
   (a) 8 avalanche photodiodes (4 sizes) from RMD Inc. $32k
   (b) Materials for mounting of the sensors $0.8k
   (c) 2 DRS4 4-ch, 6-GSample/sec Evaluation Boards from PSI $4.2k
   (d) 1 PC for the data acquisition system $1.6k

2. Shop labor for mounting of the sensors $3.2k

3. Travel $7.2k

4. **Total $49k**

4 Personnel

BNL personnel associated with this proposal are G. Atoian (TBC), M. Chiu, M. Diwan (TBC), G. deGeronimo, N. Simos (TBC) T. Tsang, Z.Li, and S. White (BNL PI).

Collaborators on this project include J. Rohlf of Boston U, J. Freeman and I. Musienko (TBC) of Fermilab, and K.T. McDonald and C. Lu of Princeton U.