ATLAS FORWARD PROTON DETECTORS: TIME-OF-FLIGHT ELECTRONICS*

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We present the custom-designed fast analog and digitizer electronics developed for the fast time-of-flight Cherenkov detectors of the ATLAS Forward Proton project at the CERN Large Hadron Collider. The electronics is designed to be radiation tolerant and deliver a timing resolution of 20 picoseconds or better per detector channel.

1. Introduction

The ATLAS Forward Proton (AFP) program aims to intercept and measure protons emitted in the very forward directions from the ATLAS interaction point (IP). Forward protons are characterized by their energy fractional loss $\xi = (E - E_{\text{beam}})/E_{\text{beam}}$ and by the four-momentum transfer squared $t = (p - p_{\text{beam}})^2 \simeq (p\theta)^2$, where E and p characterize the forward proton, and θ is its scattering angle.

A varied physics program using forward protons becomes available with AFP: single and double diffraction measurements, Pomeron structure functions, rapidity gap survival probability, double Pomeron exchange (DPE) and double photon exchange (DPhE) processes. The latter give access to anomalous quartic coupling measurements of interest to beyond-Standard-Model Physics signals.

The AFP detectors consist of two forward arms, with two detector station per arm located at 206 m and 214 m from the ATLAS IP. The detectors are housed inside so-called Roman pots, stainless steel pots that are able to move

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inside the beam pipe aperture after stable collisions are established. The pots have thin 300 μm windows facing the beam, to minimize interactions and to enable the detectors to approach the beam as close as possible to intercept protons with energy losses as low as $\xi \simeq 1.5\%$. The upper limit to the ξ-acceptance is about 15%.

Although the non-exhaustive list of AFP physics processes covers a wide range of cross sections, some of the more interesting processes are rare and require running at the highest luminosity available. Characterizing the instantaneous luminosity by the average number of interactions, μ, occurring at a bunch crossing, μ is expected to be in excess of 25 for the upcoming LHC run period and may well reach 50 or more interactions per bunch crossing.

2. Time-of-flight detector

Because single diffraction, which produces a single forward proton, is relatively common (about 10% of the total cross section), an interaction of high interest, say DP(h)E which yields two forward protons, may easily be faked by the occurrence of two single-diffraction interactions in the same bunch crossing. The only possible rejection of this background to DP(h)E processes is to measure the arrival time difference of the forward protons in the two arms with picosecond accuracy. For a genuine DP(h)E two-proton event, the arrival time difference of the forward protons $\Delta t = t_{\text{Left arm}} - t_{\text{Right arm}}$ is directly related to the interaction vertex location z_{vertex} (z measured along the beam from zero at the ATLAS IP and positive toward the 'Right' arm) as: $z_{\text{vertex}} = c\Delta t/2$. Thus, a $\sigma_t = 10$ ps time-of-flight resolution translates into a $\sigma_z = 2.1$ mm vertex resolution. The vertex location derived from fast timing is compared to the location measured from the ATLAS inner detector tracking; if the two locations differ, the protons stem from unrelated background events. Extensive simulations have shown that a 10 ps time-of-flight measurement provides a background rejection factor around 20.

The proposed AFP time-of-flight detectors consist of quartz bars positioned at the Cherenkov angle with respect to the proton directions. The Cherenkov light travels up the bars and is converted to a signal by a specialized Multi-Channel, Multi-Anode Photomultiplier Tube (PMT). It is described elsewhere at this workshop [1]. In this paper, we describe the time-of-flight electronics and trigger system.

The PMT output signal is approximately Gaussian with a 700 ps full width at half maximum (rms $\simeq$ 300 ps). Photon statistics (the mean number of photo-electrons is about 10) affect the signal amplitude but preserve the

shape precisely. The goal of the electronics is to preserve the signal shape information and derive the best possible timing of the signal, independent of the signal amplitude.

The approach chosen by the AFP timing group is low-noise amplification followed by constant-fraction discrimination (CFD) and high-precision time digitization (HPTDC) and readout, see Fig. 1 where the various components and their locations are depicted.

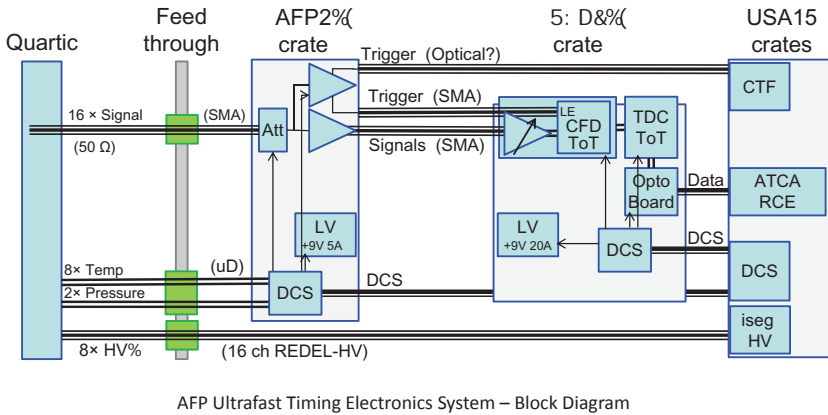AFP Ultrafast Timing Electronics System – Block Diagram

Fig. 1. A schematic diagram of the components of the fast timing electronics chain described in the text, together with their physical locations in the LHC tunnel.

Other approaches are possible, as discussed, for example, by Delagnes, Breton, and Ritt [2–4] at this workshop. Although the sampling methods described by these authors are best performing, the CFD method described here is very close to optimal, as is also shown in the overview presentation by Genat [5] at this workshop.

Beam tests (Fermilab 2012, CERN 2013) have shown that the single-channel resolution of PMT, Preamplifiers and CFD is 20 ps, limited by the PMT signal shape, statistics, and noise. Two or more sequential measurements (two or more successive quartz bars) will reduce the proton ToF resolution accordingly; four sequential measurements will provide 10 ps resolution. The beauty of the system is its modularity: the resolution can be tuned by changing the number of quartz bars in succession, while the resolution requirement per-channel is somewhat relaxed. Somewhat arbitrarily, in order to preserve the per-channel timing resolution, we require the time jitter of the electronics to be 5 ps or less.

Adjacent sequences of quartz bars cover intervals in proton energy loss ξ. It is assumed that the ξ acceptance is subdivided into 4 intervals, each individual ξ interval covered by a sequence of 2–4 quartz bars. Since the

central missing mass MM measured from the two protons is directly related to their ξ, $MM^2 = \xi_1\xi_2(2E_{\text{beam}})^2$, a selection for events in which a large missing mass is produced can be formed already at the trigger level.

3. Preamplifiers

The PMT is used at a low gain of about 5×10^4 to maximize the lifetime of the tube in the high-rate LHC environment close to the circulating beam. The typical PMT output signal at this gain is about 8 mV for 10 photoelectrons. The AFP CFD used has a dynamic range from 250–1200 mV (a new design is in the works with a further improvement anticipated in dynamic range).

In order to match the CFD dynamic range, and to provide for gain variations as a function of PMT pixel and ageing, the preamplification is done in two 20 dB stages. The first stage PA-a is located directly on the base of the PMT. The 8-channel preamplifier PCB is based on the PSA4-5043+ low-noise (NF = 0.7 dB) InGaP E-PHEMT MMIC gain block (gain 18.6 dB at 1 GHz) from `MiniCircuits.com`, see Fig. 2. The PA-a has been tested under power and demonstrated to be radiation tolerant to at least 9 kGy (LANSCE, February 2014 run with 800 MeV protons, 2.2×10^{13} p/cm^2); this dose corresponds to the dose expected at the preamplifier location for 300 fb^{-1} or three years at a luminosity of 10^{34} cm^{-2}s^{-1}.

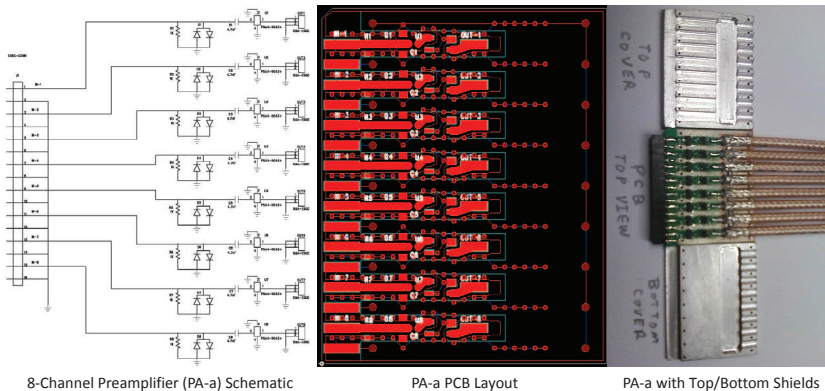8-Channel Preamplifier (PA-a) Schematic   PA-a PCB Layout   PA-a with Top/Bottom Shields

Fig. 2. The schematic diagram, layout, and photo of the low noise pre-amplifier, to be located on the photodetector base in the secondary vacuum.

The first preamplifier stage is connected by coaxial cable to the second preamplification stage (PA-b) located at floor level below the detector, where the high-energy proton flux is expected to be a factor 20 lower (the low energy neutron flux is a factor 10 lower there).

The PA-b provides DC power (5 V) to the PA-a via the coaxial connection. The PA-b further includes (in order): a programmable 3-bit attenuator (Hittite HMC288MS8 2 dB LSB GaAs MMIC, range 1–15 dB), a 2 Way-0° splitter (MiniCircuits TCP-2-33W+, −4 dB insertion loss) providing a trigger pick-off, and a ADL5611 gain block (Analog Devices, gain 22(20) dB at 1(4) GHz), see Fig. 3. The PA-b has successfully survived the same irradiation runs and doses as PA-a.
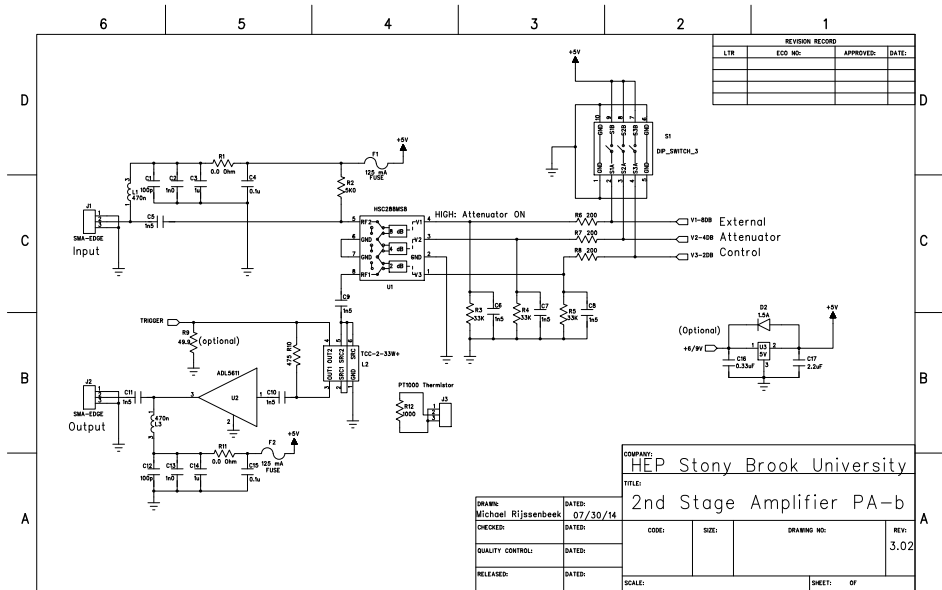

Fig. 3. The schematic diagram of the new second-stage variable-gain amplifier PA-b, to be located below the detector at floor level.

4. Trigger

A trigger board has been designed and will be produced in the near future. The design is based on the 8-channel GaAs Discriminator MMIC 'NINO' (developed and produced by CERN, see `http://knowledgetransfer.web.cern.ch/technology-transfer/external-partners/nino`), followed by programmable majority circuitry to form a 'N out of M' type trigger combination on two LVPECL outputs. The option to include a (properly timed) bunch crossing gate (LVPECL) is implemented. The PCB has been laid out but has not yet been produced.

The trigger signals from several adjacent quartz bar sequences are combined into a bit stream and sent over fast air-core coax cables to the ATLAS Central Trigger Processor. The trigger information from the two AFP arms can be used to form a large proton–proton 'missing mass' trigger and can be combined with various central ATLAS trigger terms.

5. Constant Fraction Discriminator

The Constant Fraction Discriminator principle has long be used to correct for time walk in cases where the signal fluctuates in amplitude but is constant in shape. The AFP design was initially developed for FP420 by L. Bonnet of the Université Catholique de Louvain, and was further developed for AFP by the HEP group (J. Pinfold, S.-L. Liu) at the University of Alberta at Edmonton (Alberta). The measured timewalk is 5 ps or less over the range 250–1200 mV. The design is currently revisited to obtain a larger dynamic range and to implement a time-over-threshold functionality, which will allow off-line timing corrections if so required. Moreover, the new CFD design includes an optional bunch crossing gate to reduce output rates.

A single CFD channel is implemented on a small 28×70 mm^2 daughter board, with RF I/O connectors for signal in and signal NIM out, and differential LVPECL outputs.

6. High Precision Time Digitizer

The High Precision Time Digitizer board, HPTDC, was developed by the University of Alberta. The 12-channel board uses 4 HPTDC ASICs developed and produced by CERN in 0.25 μm CMOS technology (HPTDC, J. Christiansen *et al.*, `http://tdc.web.cern.ch/tdc/hptdc/hptdc.htm`). The four ASICs are controlled by an on-board FPGA which also handles the flow of data and controls. This and previous versions of the HPTDC board have been used successfully at various beam tests. The HPTDC, and new developments were presented by Pinfold at this workshop [6].

The intrinsic resolution of the current HPTDC is 16 ps, which is a significant contributor to the per-channel resolution. However, new HPTDC ASIC development with smaller feature size are ongoing at CERN and may lead to significant improvements in the near future. Note that the 16 ps resolution of the HPTDC is per channel and that the contribution for a system of four quartz bars in sequence would only be 8 ps.

The radiation tolerance of the HPTDC is not guaranteed. The HPTDC ASIC is expected to be radiation tolerant to a degree sufficient for it to be located on the tunnel floor, near the detectors. The FPGA firmware must be re-designed to provide the appropriate checking of HPTDC registers for

upsets. Moreover, the FPGA itself has to be radiation tolerant, which can be done by choosing a radiation-hard part (expensive!) or going to a fuse-programmable part. Alternatively, the FPGA can be programmed to do self-checking and organized with majority decisions in critical paths. It is the latter choice that will be pursued.

7. Reference Clock

A major component of any time-of-flight system using two widely separated detector arms (424 m apart measured along the beam line), is a synchronizing Reference Clock. As for other components, the requirement is that the two local detector clocks are synchronized to well within 5 ps.

The University of Texas group (A. Brandt, V. Shah, *et al.*) has developed a prototype Reference Clock based on a design originally by SLAC. Every Daughter Clock sends its signal to a central Reference Clock which produces a DC phase error signal that is read (on the same cable) by the Daughter Clock. The Daughter Clock adjusts its phase until the phase error signal is zero.

The design is not fully complete at this time but initial tests indicate the desired performance can be reached.

In addition to the synchronized local clock, clock fanouts at the local detectors are required. We intend to implement these with high performant LVPECL Clock FanOut buffers from Micrel.

8. Data acquisition

The Data Acquisition system currently foreseen is based on the Reconfigurable Cluster Element (RCE) computer daughter boards in the ATCA telecom standard. This system has successfully been employed for the testing of the ATLAS Intermediate B-Layer silicon pixel detectors. Because the same silicon sensors are used for the AFP tracker, the RCE-based DAQ system can be used essentially without any new development. However, the HPTDC board has to be interfaced to the RCE readout. This requires new FPGA firmware (also required for radiation tolerance!) as well as additions and modifications to the RCE software.

Because the RCE hardware is located in a low radiation and accessible area near the ATLAS detector, radiation tolerance is not an issue for the DAQ.

9. Conclusion

We presented a complete fast electronics chain that will preserve the 20 ps per channel time resolution required for the AFP time-of-flight detectors. We presented a fast Trigger scheme for the AFP detectors which incorporates a rough measure of the proton energy loss for use in the ATLAS Central Trigger Processor. We discuss radiation tolerance requirements and how they are met in the proposed chain.

REFERENCES

[1] A.G. Brandt, "Fast Timing System for LHC Time-of-flight Detector Speakers", talk at the Workshop on Picosecond Photon Sensors for Physics and Medical Applications, Clermont-Ferrand, France, March 12–14, 2014.

[2] E. Delagnes, *Acta Phys. Pol. B Proc. Suppl.* **7**, 685 (2014) , this issue.

[3] E. Breton, *Acta Phys. Pol. B Proc. Suppl.* **7**, 673 (2014) , this issue.

[4] S. Ritt, "A New Timing Calibration Method for Switched Capacitor Array Chips to Achieve Sub-picosecond Resolutions", talk at the Workshop on Picosecond Photon Sensors for Physics and Medical Applications, Clermont-Ferrand, France, March 12–14, 2014.

[5] J.-F. Genat, "Signal Processing for Fast Photo-detectors", talk at the Workshop on Picosecond Photon Sensors for Physics and Medical Applications, Clermont-Ferrand, France, March 12–14, 2014.

[6] J. Pinfold, "Plans for a Picosecond HPTDC", talk at the Workshop on Picosecond Photon Sensors for Physics and Medical Applications, Clermont-Ferrand, France, March 12–14, 2014.