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QUARTIC — THE PRECISION TIME-OF-FLIGHT COUNTER FOR THE ATLAS FORWARD PHYSICS PROJECT*

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Precise TOF counters are employed by AFP to reduce pile-up background in the forward proton spectrometers. It is expected that at the highest LHC luminosity up to ~ 35 interactions occur at the same bunch crossing in ATLAS. A precision of the order of few mm (~ 10 ps) or better is required to adequately distinguish the vertex of interest — from which the unbroken scattered protons originate — from other pile-up vertices, with good efficiency. The development and testing of the QUARTIC precision TOF detector and its readout is described. This detector utilizes fused-silica radiators readout by Micro-Channel Plates Photomultipliers. The front-end readout electronics is based on the High Precision Time to Digital Converter (HPTDC).

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1. Introduction

Under the auspices of the ATLAS Forward Physics (AFP) group two major detector upgrades are currently under investigation, which will extend the ATLAS coverage in the forward direction and provide unique possibilities to improve the physics capabilities of the experiment: the Roman Pots at 220 meters (RP220 [1]) and the Forward Proton tagging detector at 420 metres (FP420 [2]). Fig. 1 shows the deployment of the approved (ALFA, LUCID, ZDC) and planned (AFP) forward detector systems for ATLAS.

The role of the planned AFP detector systems is to provide proton tagging and triggering capabilities in the very forward direction. This capability is required in, for example, the measurements of Central Exclusive

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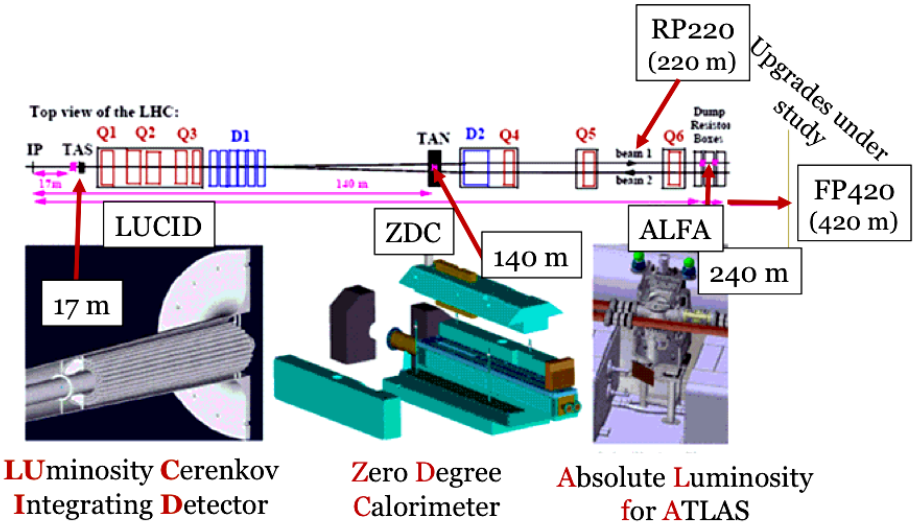

Fig. 1. The ATLAS Forward Detectors and their position relative to the interaction point.

Production (CEP), namely the process $pp \to pXp$. Here the two protons loose a fraction ξ_1 and ξ_2 of their initial momentum, respectively, but do not break up.

The central system X is observed via its decay products in the central detector with no hadronic activity observed in between (rapidity gap). The mass of the central system is then given by $M_X^2 = \xi_1 \xi_2 s$. The combination of RP220 and FP420 (AFP) can measure fractional proton momentum losses $0.002 < \xi < 0.2$ which converts into a sensitivity of $M_X > 30$ GeV$/c^2$, with a resolution on M_X at the percent level if both protons are seen at 420 m.

The physics case for AFP has been discussed in detail in the AFP Letter of Intent to ATLAS, which is largely based on the FP420 R&D report [3]. The initial FP420 R&D program was endorsed by the LHCC in 2005: "The LHCC acknowledges the scientific merit of the FP420 physics program and the interest in its exploring its feasibility. The addition of AFP to ATLAS enables the LHC to operate as a gluon–gluon, photon–photon and photon–gluon collider with known centre-of-mass energy in the range of 70 GeV to 1.4 TeV. AFP provides a rich QCD and electroweak physics program extending the current ATLAS physics capabilities."

Photon–photon physics complements the ATLAS strategy for precision measurements of anomalous couplings and the search for supersymmetric (and other BSM) charged particles. Furthermore, gluon–gluon physics allows the study of Higgs boson in the CEP channel. In addition to an event-by-event mass measurement of about 3 GeV, the observation of a Higgs boson in this channel is equivalent to a quantum number measurement since resonance production is suppressed for particles with $J^{\mathrm{PC}} \neq 0^{++}$.

The detectors of the ATLAS Forward Physics (AFP) project must be capable of operating at the LHC design luminosity $L \sim 10^{34}$ cm^{-2} s^{-1} in order to be sensitive to femtobarn level cross-sections in the central exclusive channel [proton–X–proton]. At these luminosities overlap background from two single diffractive events superimposed with a central hard scatter ([p][X][p]), as shown in Fig. 2 (a), becomes a significant concern, especially in di-jet final states. The 2-fold overlap coincidence backgrounds, shown in Fig. 2 (b) and (c), also must be considered. But, as they scale with Luminosity L^2 instead of L^3 they matter less in the high luminosity limit.

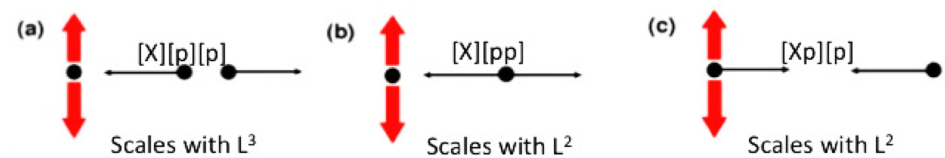

Fig. 2. A schematic diagram of overlap backgrounds to CEP: (a) [p][X][p], three interactions, one with a central system, and two with opposite direction single diffractive protons (b) [pp][X], two interactions, one with a central system, the 2nd with two opposite direction protons (c) [p][pX], two interactions, one with a central system and a proton, the 2nd with a proton in the opposite direction.

2. Reducing backgrounds with fast TOF counters

High-precision Time-of-Flight (TOF) detectors at 220 and 420 m can be used to obtain a large reduction in overlap (pile-up) backgrounds [4]. We need only to measure the relative arrival time of the two protons, $\Delta t = t_{\mathrm{L}} - t_{\mathrm{R}}$. Under the assumption that they originate from the same event, the z-position of that event can be calculated as $z_{pp} = c\Delta t/2.0$. The uncertainty on z_{pp} is $\delta z_{pp} = c\delta t/\sqrt{2}$, where δt is the (r.m.s.) time resolution of the proton measurement. For example, $\delta t = 10$ ps gives $\delta z_{pp} = 2.1$ mm. We then require a match between z_{pp} and the vertex position from the central detector, z-vertex, which is known with very good precision (~ 50 μm) [5].

We have calculated the background rejection for the three overlap cases, shown in Fig. 2 (a) — [p][p][X], (b) — [pp][X] and (c) — [pX][p]. For example, if $\delta t = 20$ ps ($\delta z_{pp} = 4.2$ mm) and the spread in interaction points is $\sigma z \sim 50$ mm [4], we obtain a rejection factor of 21 for the first two cases and 15 for the third if the vertex measurement from proton TOF is required to fall within ± 4.2 mm ($\pm 1 \times \delta z_{pp}$) of the vertex measured by the central detector.

Case (a) dominates at high luminosity and consequently for $\delta t = 10$ ps, we would be able to obtain a rejection factor of greater than 40 enabling FP420 to handle the large overlap backgrounds at the design luminosity. Two types of TOF counters will be utilized for background reduction by the AFP project, GASTOF (Gas Time-of-Flight) and QUARTIC (QUARtz TIming Cerenkov).

3. The QUARTIC TOF detector

The QUARTIC detector, which utilizes Fused Silica (FS) bars as radiators, is a joint development effort of University of Alberta, Fermilab, and University of Texas, Arlington. Figure 3 (left) shows the concept: a proton passing through the silica bars radiates photons that are measured by the MCP-PMT. The QUARTIC detector design, a 4×8 array of bars 15 mm in length with a 6 mm $\times$ 6 mm cross-section is mounted at the Cerenkov angle, $\theta_c \sim 48^\circ$, minimizing the number of reflections as the light propagates to the MCP-PMT through an air-filled aluminized light guide. Air light guides are being considered as well as with long silica bars since one can avoid the time dispersion, from the wavelength dependence of the index of refraction but at the cost of less light. The final detector configuration is still under review. Figure 3 (middle) shows the Alberta single row prototype used in the 2008 CERN TB. The Fig. 3 (right) is a photograph of the Alberta prototype fused silica fibre radiator bars.

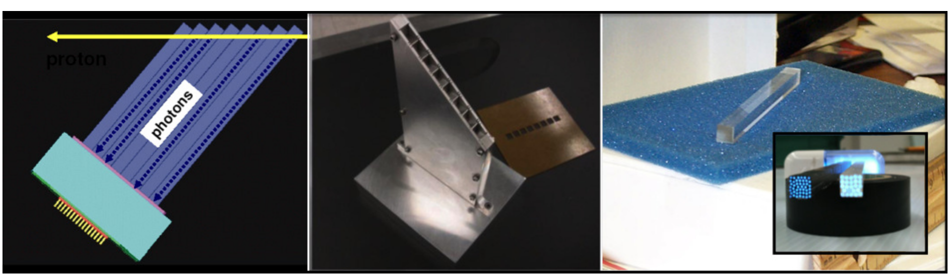

Fig. 3. (Left) Conceptual drawing of a QUARTIC detector, with four rows of eight 15 mm long bars, followed by air light guides to the MCP-PMT. (Middle) A photograph of the Alberta prototype detector used in the 2008 CERN test-beam. (Right) Prototype radiator constructed from fused silica fibres.

The GASTOF and QUARTIC detectors have complementary features and we are proposing to use both in AFP. One GASTOF detector will be located in its own beam pipe pocket after the first silicon detector pocket. The two QUARTIC detectors, providing 16 independent measurements of the TOF of the detected proton, will be positioned in another pocket after the final silicon tracking detector. The overall resolution of the QUARTIC detector system is $\sigma_{\text{QD}}/\sqrt{16}$, assuming all measurements are independent, where σ_{QD} is the temporal resolution of a measurement made with a single (identical) QUARTIC bar. The use of multiple independent measurements allows the resolution requirement of the actual time measurement made by each QUARTIC measurement to be relaxed by a factor of ~ 4.

4. QUARTIC frontend electronics

The readout electronics must be fast with low noise to attain the best timing resolution as shown in Fig. 4 a single electronics channel consists of the following elements. First, there is an Amplifier and Constant Fraction Discriminator (CFD) stage. The CFD was initially designed by Louvain but has now been updated and improved by the Alberta group. The CFD works with rise times as short as 150 ps and to be insensitive to amplifier non linearity and saturation. A Mini-module approach is utilized for the amplifier-CFD stage. At this time the 12 mini-modules are mounted on a NIM mounted card to create a 12-channel NIM module. The CFD mini-module are tuned to Burle and Hamamatsu rise times to give a resolution of less than ~ 10 ps for ≥ 4 PEs.

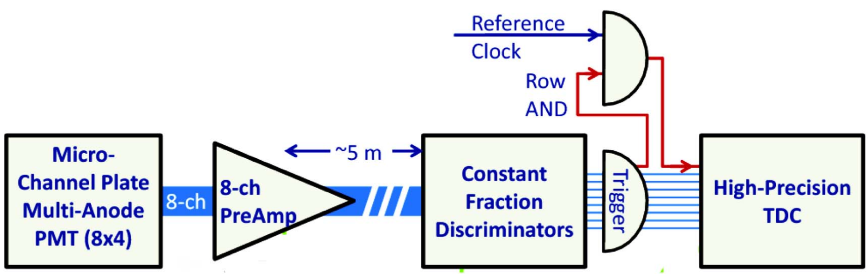

Fig. 4. Schematic of the reference timing system as described in text.

Second, we have the TDC stage. The baseline solution for the final detector utilizes the 32 channel High Precision Time to Digital Converter chip (HPTDC) that is reasonably radiation hard and LHC compatible. The number of channels falls to 8 when the chip is run in high precision mode with 25 ps least bit temporal size. The Alberta group has designed and built an 8 channel HPTDC prototype board with a 12 ps resolution with pulser signals. In order to obtain a throughput to accommodate the maximum expected 'per bar' 15 MHz hit rate at the LHC, two modifications have been made to the HPTDC board. First, the HPTDC chip board will run at a clock speed of 80 MHz. It has been demonstrated that this increased speed does not affect the time resolution although is understandably increases the power consumption of the HPTD board. The 8 high precision HPTDC channels are ganged in twos reducing the number of channel to 4 per chip. One of these 4 channels is used to accommodate the reference timing. A timing board with 3 HPTDCs is currently being designed.

4.1. Reference timing

The final component of the electronics is the low jitter clock signal required to measure the time difference between the two outgoing protons; the time difference of each proton with respect to a common clock is measured, so that this clock must have low jitter (less than about 10 ps). The reference timing stabilization circuit shown in Fig. 5 uses a phase locked loop feedback mechanism that compares the master frequency of 400 MHz with the signal sent via a coaxial cable to the detector station. A voltage controlled oscillator (VCO) launches a signal down the cable where it is reflected and sent back. The returned signal is then compared to an external RF reference to synchronize it with the reference. At the end of the cable the signal is sampled with a directional coupler where it is compared with the 400 MHz master reference in the mixer. The result is a DC voltage level that is fed back to the VCO to maintain a constant number of wavelengths in the cable.

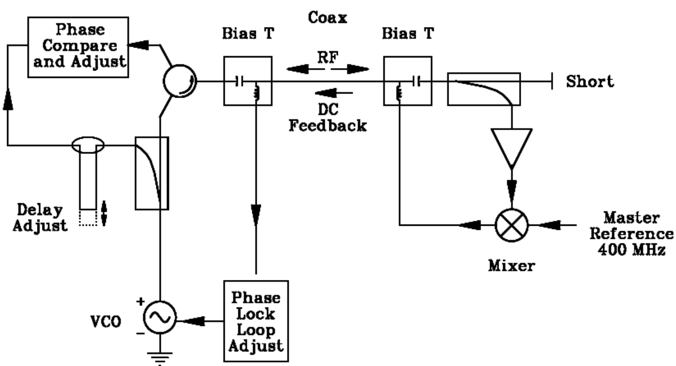

Fig. 5. Schematic of the reference timing system as described in text.

Although high quality coaxial cable will be used, it will still attenuate the 400 MHz signal by 4 to 6.5 dB depending on cable quality. The mixer will require +7 dBm (5 mW) to drive it, so a low noise amplifier will need to boost the signal by an amount to recover the cable and power coupling loss. Low frequency amplifiers will also be needed to increase the voltage controlling the VCO. This system is based on a design developed at the Stanford Linear Accelerator Center (SLAC); initial tests at SLAC performed by Joe Frisch of SLAC, a consultant on our project obtained sub-picosecond accuracy. The timing circuit outputs a stabilized 400 MHz signal, which will then be converted to a 40 MHz square wave for input into the HPTDC board, possibly using a multivibrator circuit. The design and fabrication of the reference timing and the interface to the HPTDC board is another area of detector development for this MRI proposal.

5. Test performance

We have utilized a prototype detector to study the QUARTIC approach to fast timing for FP420/AFP at various TB venues: Fermilab, September 2006, March + July 2007 and November 2010; CERN, October 2007, June 2008 and August 2010. A laser test set up was installed at the University of Texas in Arlington (UTA) in 2009 for bench testing of the device.

The improvement in timing resolution with the number of independent measurements ($\sqrt{N}$) was demonstrated using the UTA laser test stand. In this case, measurements were made of the time difference for three separate fibers used to excite the FS bars. In this case, the laser light gave rise to 100 PEs in each bar. In this case the time resolution obtained for each bar was ~ 16.2 ps. The time differences measured w.r.t. a reference tube, were corrected for T_0 offset, averaged and a new time difference w.r.t. reference tube of 10.3 ps was obtained. However, this improvement must be demonstrated using realistic signals generated with actual particles at a test beam.

Using CERN TB in 2008 the time difference between two 9 cm quartz bars after the constant CFD was measured to be 56 ps, implying a single bar resolution of ~ 40 ps for about 10 PEs when readout through the full electronics chain. The measured efficiency of each bar was high, greater than 95%, and uniform across the bar. The test in August 2010 with a the Alberta QUARTIC prototype and tuned electronics obtained a ~ 30 ps per bar resolution. The use of silicon photomultipliers (SiPMs) rather than MCPMTs as readout was tested at the test beam at Fermilab in November 2010. A resolution of 25–30 ps per bar resolution was observed using the Alberta CFD with a fast scope.

6. Design challenges

We need to establish if the MCP-PMTs are capable of coping with the large expected rates at the LHC: up to 15 MHz in a 6 mm $\times$ 6 mm pixel of the MCP-PMT. The limiting quantity is not actually the rate, but the current in the tube. In order to keep the current at tolerable levels, we can lower the gain; have fewer PEs — although precise timing needs as many PEs as possible — and use MCP-PMTs with smaller pore size.

When the current demanded of the tube is too high the gain is reduced — this is called saturation. Using 1 MHz for low luminosity condition and 15 MHz for high luminosity, with a gain of 5×10^4 and 10 PEs expected for our detector, we obtain, using laser test stand measurements, current limits of 0.08 μA/1.2 μA, respectively (in a 0.36 cm^2 pixel). At these currents saturation is pronounced. Luckily, Photonis has fabricated a 'Planacon' MCP-PMT with a factor of ten times higher current capability that should meet our rate requirements.

Another experimental challenge is the limited lifetime of the MCP-PMT. The lifetime of the photocathode is primarily limited by damage from positive ions that is believed to be proportional to extracted charge: Q/year $= 1 \times 10^7$ s/year. In Phase I the extracted charge is 0.8 to 2.4 C/year (in a 0.36 cm^2 pixel). In Phase II the extracted charge is five times greater.

Fortunately we have a number of options for the improvement of the lifetime limitation of our MCP-PMTs. First, a number of improvements have already been demonstrated: we can place an ion barrier in the MCP-PMT, this gives a factor 5 to 6 lifetime improvement; electron scrubbing of the MCP-PMT yields a factor 5 to 10 lifetime improvement; and, utilization of the Z-stack arrangement of the MCP promises a factor of ten lifetime improvement [6]. In addition, ARRADIANCE has developed techniques for coating MCPs with 'nano-films'. This technique can be used to improve tube lifetime, although this has still to be demonstrated, and promises a factor of 10 improvement. Various combinations of these should give multiplicative improvement factors.

7. Conclusion

We have demonstrated the 10 ps time resolution required of the QUARTIC TOF detectors by the AFP project, but more work is required to determine the final parameters of the detector and electronics design. We are pursuing a R&D project to solve the lifetime problem for MCPs at the highest luminosities. To that end, we are working with three major manufacturers in this area: PHOTONIS, PHOTEK and ARRADIANCE.

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