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The ATLAS Forward Proton Detector (AFP)

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Abstract

The ATLAS Forward Proton (AFP) detector will identify events in which one or two protons emerge intact from the proton-proton collisions at the LHC. Tracking and timing detectors will be placed 2-3 mm from the beam, 210 m away from the ATLAS interaction point. The silicon-based tracker will provide momentum measurement, while the time of flight system is used to reduce the background from multiple proton-proton collisions. The study of soft and hard diffractive events at low luminosities ($\mu \approx 1$) is the core of the AFP physics program. This paper presents an overview of the project with particular emphasis on the qualification of the pixel and timing systems.

Keywords: high energy physics, AFP, 3D sensors, time-of-flight, radiation hardness

1. Introduction

The ATLAS Forward Proton (AFP) project [1] promises to extend the physics reach of ATLAS [2], by enabling the identification of protons that emerge intact from the LHC proton-proton collisions at very low angles. Such processes are typically associated with elastic and diffractive scattering, where the proton radiates a virtual colorless object (Pomeron). Specially interesting are hard diffractive events, which combine perturbative and non-perturbative QCD processes.

ATLAS currently has a forward detector system, ALFA [3], based on scintillator fibers placed in Roman pots close to the LHC proton beam at 240 m from the ALTAS interaction point. However, ALFA is designed to measure elastic scattering in a low luminosity environment ($\mu < 1$) and is not optimized for diffractive measurements. The AFP acceptance, though limited by the LHC collimators, substantially improves the coverage provided by ALFA in a wide range of resonance mass [4]. Furthermore, a Time-of-Flight (ToF) system would enable AFP to conduct measurements at high instantaneous luminosities, since it will provide information on the diffractive vertex position.

Rapidity gap studies have been carried out by ATLAS to gain insight into the nature of the Pomeron and test QCD predictions [5]. However, these analyses can be greatly improved by the addition of a forward proton tagging detector. Proton tagging removes the ambiguity of a rapidity gap tag, which suffers from background due to low multiplicity non-diffractive events.

The core of the AFP physics program for the first year after installation is based on low luminosity runs. In this context, single diffractive events, in which one proton emerges intact from the scattering (one proton tag), can be studied. Specially interesting are the associated production of vector bosons, which is sensitive to the quark content of the diffractive parton distribution function (PDF), and di-jet production [6], which is also sensitive to perturbative QCD predictions.

In double Pomeron exchange events, both protons in the final state emerge intact. The lower rate of this process is compensated by the double tag requirement, which provides larger bakground rejection. The associated production of di-jet, γ+jet [7] and jet-gap-jet [8] events enable tests of QCD evolution as well as a better determination of the partonic structure of the Pomeron. Without AFP, single, and double diffractive events would be difficult or impossible to study. A second AFP phase, in which the detector would be operated during high luminosity runs, is being considered.

The detector, discussed in the following sections, will consist of a tracking system based on silicon pixel sensors located in two Roman pots at either side of the ATLAS interaction point for momentum measurements, and a time of flight (ToF) detector. The ToF is not essential for the first phase program, but would be critical during high luminosity operation to reduce the background from multiple proton-proton collisions. The timing baseline detector consists of quartz bars, though a detector based on silicon [9] or diamond [10] sensors is also being considered. Both the timing and tracking systems would be readout with the RCE (Reconfigurable Cluster Element) system developed at SLAC, which was already used in ATLAS for the Insertable B-Layer (IBL) module qualification. The foreseen date of installation of AFP is during the LHC shutdown of December 2016.

2. AFP Tracker

The current AFP design foresees a high resolution pixelated silicon tracking system placed at 210 m from the ATLAS interaction point (IP). Combined with the magnet systems of the LHC accelerator, the AFP tracker will provide the momentum measurement of the scattered protons [11]. The tracker will consist of four units, each composed of five pixel sensor layers, which will be placed in Roman pots, two on each side of the ATLAS IP.

To increase the physics sensitivity the silicon sensors have to be placed as close as possible to the proton beam. The current system foresees a distance of $3-2$ mm between the beam and the tracking sensors. Thus, one critical requirement of the AFP pixel detector is to minimize the inactive edge of the pixel device. Though the program for the first year of operation will be carried out in special low luminosity runs, the tracker is required to sustain high radiation doses (about 3×10^{15} n_{eq}/cm^2 for 100/fb integrated luminosity), in view of possible later high luminosity runs. Specially challenging is the non-uniform nature of the dose distribution expected on the sensors [12].

In 3D pixel sensors, n- and p-type column-like electrodes penetrate the substrate defining the pixel configuration. Though the fabrication process is complex, the technology is less demanding in terms of bias voltage and cooling than the standard planar approach, and the reduced drift path makes 3D devices more radiation hard. In recent years significant progress has been made in the development of 3D sensors, which culminated in the sensor production for the ATLAS IBL.

The AFP sensors will be based on the 3D double sided sensors developed by CNM (Barcelona) and FBK (Trento) for the IBL [15]. The sensors feature an array of 336×80 pixels with a pixel size of 50×250 μm^2. The tracker will thus satisfy the AFP requirement of 10 μm spacial resolution in the short pixel direction [12]. The pixel readout electronics will be the FE-I4 [15]. The sensors are DC coupled to the chip with negative charge collection. Each readout channel contains an independent amplification stage with adjustable shaping, followed by a discriminator with independently adjustable threshold. The chip operates with a 40 MHz externally supplied clock. The time over threshold (ToT) with 4-bit resolution together with the firing time are stored for a latency interval until a trigger decision is taken. The FE-I4 chip can also send a trigger signal.

The AFP module prototypes built so far use 3D sensors from the IBL production. These sensors suffer from a large ($\approx$ 1.5 mm) inactive edge on the side which will be closest to the beam in the AFP configuration (which is not relevant for the IBL modules, but critical for AFP). This large inactive edge was included in the IBL design for the single sided ("full-3D") technology which requires a bias tab to provide the voltage to the ohmic side. The single sided technology was not included in the IBL, however, the common design mask used, introduced the inactive region in the CNM and FBK sensors. To reduce the inactive edge, different dicing techniques have been investigated. A standard diamond saw cutting procedure has been applied to produce the AFP prototypes used in the following studies.

3. AFP Tracker Performance

As mentioned in Section 2, the 1.5 mm dead area of the AFP sensors was reduced to $\approx$ 200 μm by using a diamond saw cut. In order to measure the effective active edge after dicing, beam tests were conducted at DESY with 5 GeV electrons in July 2013. Beam particle trajectories were reconstructed using the high resolution EUDET telescope [16]. The devices under test were placed between the Mimosa telescope planes. The threshold of the devices was tuned to 2000 electrons (e) and the bias voltage applied was 30 V. Typical noise levels of the CNM and FBK devices were 150 e. The tests were performed at room temperature. Data presented here were recorded at perpendicular incident angle. The hit efficiency is determined from extrapolated tracks on the devices, after track quality cuts have been applied. A hit on the device under test is searched for in a 3×3 pixel window around the track position.

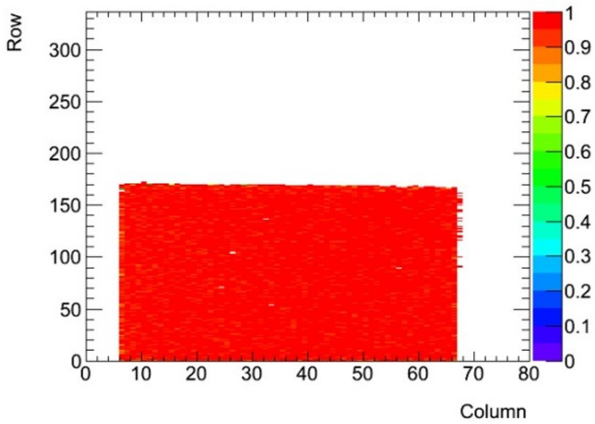

Figure 1: Overall hit reconstruction efficiency of an AFP prototype in the region of the edge slimmed for AFP.

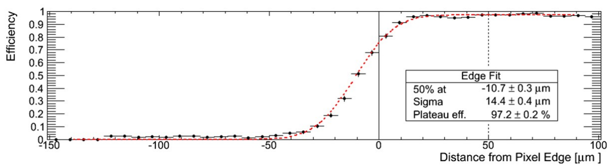

Figure 2: Hit reconstruction efficiency along the edge slimmed for AFP. The combined effect of track resolution and the fact that charge is collected beyond the last pixel row explains the tail to the left.

Figure 1 shows the efficiency of one CNM prototype (S5-R7). Since the active area of the FE-I4 devices is larger than the Mimosa sensors of the telescope, the reconstructed tracks extrapolate to a fraction of the active area of the AFP devices. The beam was centered on the area corresponding to the slimmed side of the sensor. The overall hit reconstruction efficiency of the four devices tested was above 97%. Note that the efficiency increases by 1% if a small indecent angle is used instead [15], as it is indeed planned for the AFP tracker.

The region close to the edge that was diced for AFP was studied in greater detail. Figure 2 shows the projection of the the hit reconstruction efficiency in all the columns along the last two pixel rows and into the uninstrumented area toward the physical edge of the sensor. The result shows excellent efficiency until the last pixel row. For FBK devices the charge collection region extended further into the physical edge [17]. In both cases the AFP requirement of slim edges of 150 μm was achieved.

Initial tests of non-uniformly irradiated 3D sensors produced at CNM were presented in [18]. These studies showed good efficiency after a non-uniform irradiation with maximum dose of 4×10^{15} n_{eq}/cm^2. Further studies have been carried out recently. CNM and FBK AFP prototypes with slim edges where irradiated to 3×10^{15} n_{eq}/cm^2 at Karlsruhe Institute of Technology [19] through an aluminum mask with 4 mm slit in order to produce a very non-uniform irradiation profile. The results, presented in detail in [17], show that the 3D devices can sustain the bias voltages (of the order of 100 V) needed to achieve excellent efficiency in the irradiated region.

4. AFP Timing System

The time of flight system of the AFP detectors is essential to reduce background from multiple proton-proton collisions when running at high-luminosity. However, the ToF information would also be useful to reduce the background at lower luminosities. Furthermore, in order to gain operational experience with the system, it is critical to study its performance during the first phase of AFP.

The timing system should be radiation tolerant and provide an acceptance that covers the tracking detector ($\approx 2 \times 2$ cm^2) and segmentation for multi-proton events. When operating at high luminosity, a timing resolution of 10 ps is required [12]. The baseline timing system, called QUARTIC (Quartz Timing Cherenkov), consists of quartz radiator bars coupled to micro-channel plate photomultiplier tubes (MCP-PMT) [20]. Other timing technologies are also under evaluation, including diamond and silicon detectors.

The QUARTIC bars are oriented at the average Cherenkov angle with respect to the incident proton. Thus, the multiple timing measurements of the Cherenkov radiation that arrives to the MCP-PMT are combined to achieve the desired resolution. The current ToF design foresees an array of 4×5 bars, which combines the five column measurements and provides a ≈ 5 mm segmentation. The MCP-PMT signal is amplified, sent to a constant-fraction discriminator (CFD) and digitized by a high-precision TDC chip (HPTDC [21]).

The quartz detector bar design, originally optimized for a Hamburg beam-pipe, has been recently modified for a Roman pot installation. Since there is less space in the Roman pot, the new design includes two bars connected at 90° with a 45° aluminized elbow. The rest of the timing design is unchanged. The QUARTIC system has been studied at beam tests during the last years. A summary of the main results is presented in the next section.

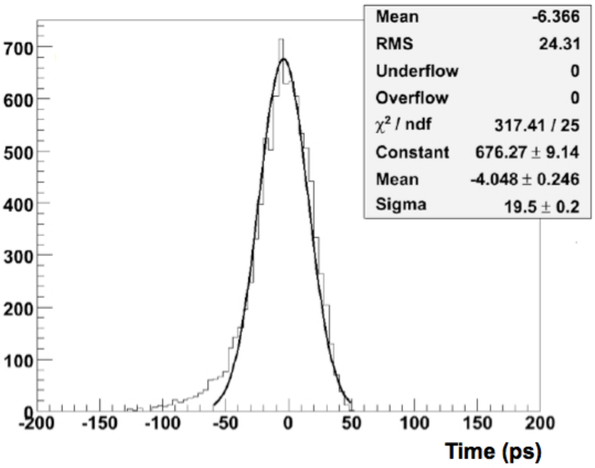

Figure 3: Time difference between a reference signal and the average time from six quartz bars. After subtracting the contribution of the reference signal a 14 ps timing resolution is obtained. The measurements were made using straight bars and a fast oscilloscope to readout the CFD.

5. AFP Timing System Performance

The main concern regarding the lifetime of the MCP-PMT system is the performance degradation of the photocathode caused by back-scatterred positive ions. In order to suppress the creation of positive ions, an atomic layer deposition technique (ADL) is used to coat the MCPs. The next generation of ALD MCP-PMTs is expected to maintain excellent performance to integrated anode charges of 10 C/cm^2, which corresponds to 100/fb.

The performance of the timing system has been extensively studied with particle beams at Fermilab and CERN [20]. Figure 3 shows the time difference between a reference signal from a silicon photomultiplier (SiPM) and the average time from six quartz bars, using a 120 GeV proton beam at Fermilab in 2012. The CDF signal was read out by a fast oscilloscope. After subtracting the contribution of the reference signal, a 14 ps timing resolution is obtained. The measurements were made using straight bars. Replacing the oscilloscope with the HPTDC degrades the overall resolution to 26 ps, but the increase is dominated by the HPTDC resolution of the SiPM, while the HPTDC resolution is smaller than the single bar resolution and has little effect on the 6-bar QUARTIC measurement.

6. Conclusions

AFP is planning to carry out a physics program during the ATLAS run 2 data taking period. The first phase of the program, to be performed during low luminosity runs, will be devoted to soft diffraction and gaining experience with the AFP timing system. A second AFP phase, in which the detector would be operated during the high luminosity runs, is being considered. The AFP tracking system is based on 3D pixel sensors readout by the FE-I4 front-end chip. Tracking prototypes with 150 μm slim edges have shown excellent hit reconstruction efficiency up to the pixel row closest to the edge. Non-uniformly irradiated samples provided high efficiency in both non-irradiated and irradiated areas. The AFP sensor productions are ongoing. The timing system, critical for the high luminosity program, will be based on quartz bars coupled to MCP-PMTs. During the first phase of the AFP program, the timing system performance will be evaluated. The QUARTIC design has been adapted to be operated in Roman pots, and the timing performance of 14 ps has been achieved at beam tests. A full system integration (tracking and timing) AFP testbeam is planned for November 2014.

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