Module production of the one-arm AFP 3D pixel tracker

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Abstract: The ATLAS Forward Proton (AFP) detector is designed to identify events in which one or two protons emerge intact from the LHC collisions. AFP will consist of a tracking detector, to measure the momentum of the protons, and a time of flight system to reduce the background from multiple proton-proton interactions. Following an extensive qualification period, 3D silicon pixel sensors were selected for the AFP tracker. The sensors were produced at CNM (Barcelona) during 2014. The tracker module assembly and quality control was performed at IFAE during 2015. The assembly of the first AFP arm and the following installation in the LHC tunnel took place in February 2016. This paper reviews the fabrication process of the AFP tracker focusing on the pixel modules.

Keywords: Large detector systems for particle and astroparticle physics, Particle tracking detectors

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1 Introduction

The ATLAS Forward Proton (AFP) [1] detector extends the physics reach of ATLAS [2] by enabling the identification of protons that emerge intact and at very low angles from the Large Hadron Collider (LHC) proton-proton collisions. Such processes are usually associated with elastic and diffractive scattering. However, the AFP physics program ultimately aims to perform searches for new physics by exploring central exclusive production.

The AFP detector will consist of high resolution pixel silicon tracker modules combined with a time-of-flight (ToF) system, placed at about 210 m from the ATLAS interaction point (IP) and at 2-3 mm from the LHC beams. The tracking detector measures the proton momentum and determines their fractional energy loss while the timing system is used to reduce the background from pile-up events. The detector systems will be placed in Roman Pot stations.

The AFP detector is being installed in two stages. In the end-of-year 2015-2016 LHC shutdown, two tracker units have been placed in two Roman Pot stations at one side of the IP. Since installation, the “one-arm” AFP detector has been operated during special runs with dedicated beam conditions. The full system with timing detectors, four tracker units and a total of four Roman Pot stations is planned to be completed during the extended end-of-year 2016-2017 shutdown. To fully exploit the AFP physics potential the ultimate goal is to operate the detector under regular beam conditions during LHC Run 2, if a safe operation of the detector is demonstrated.

Section 2 describes the one-arm AFP tracker and its components. The sensor productions are presented in section 3. The module construction and qualification is detailed in section 4, while the integration and first operation of the tracker is briefly reported in section 5. Summary and conclusions are presented in section 6.
2 Description of the AFP Tracker

The AFP tracker, combined with the magnet system of the LHC accelerator, provides the momentum measurement of the scattered protons [1]. In order to fulfill its physics goals, the tracker is required to provide a position resolution of 10 \( \mu \text{m} \) per four-plane station in the horizontal direction and 30 \( \mu \text{m} \) in the vertical one [1]. Furthermore, the inactive edge of the tracker modules have to be minimized to increase the detector acceptance. Thus the pixel devices are required to have a slim edge of 100-200 \( \mu \text{m} \). To be able to operate AFP during normal LHC runs in Run 2 (expected to deliver 100/\( \text{fb} \)), the tracker is required to sustain a non-uniformly distributed fluence up to \( 3 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2 \). Finally, the AFP tracker has to be able to provide a trigger signal, since in the one-arm operation no timing system is installed. The signal should arrive to ATLAS within the level 1 time window.

Following an extended qualification period [3, 4], 3D silicon pixel sensors were selected for the AFP tracker since they were shown to fulfil the above requirements. The AFP sensors are based on the 3D double-sided technology developed by CNM (Barcelona) for the ATLAS IBL project [5, 6]. The processed wafers are 100 mm diameter, float zone, p-type, with \(<100>\) crystal orientation, 230 \( \mu \text{m} \) thickness, and a high resistivity (20 k\( \Omega \text{cm} \)). Columnar electrodes, 12 \( \mu \text{m} \) wide, are obtained by Deep Reactive Ion Etching (DRIE) and dopant diffusion from both wafer sides, \( \text{n}^+ \) columns from the front side, and \( \text{p}^+ \) columns from the back side. Both column types stop about 30 \( \mu \text{m} \) before reaching the opposite side. The substrate bias is applied from the back side. The pixel configuration consists of two \( \text{n}^+ \) electrodes connected by a metal line to a readout pad, surrounded by six \( \text{p}^+ \) columns which are shared with the neighbouring pixels, defining the \( 50 \times 250 \mu \text{m}^2 \) pixel geometry. The \( \text{n}^+ \) columns are isolated with \( \text{p}^+ \) stop implants. The edge isolation is accomplished with a combination of a \( \text{n}^+ \) 3D guard ring, which is grounded, and \( \text{p}^+ \) fences, which are at the high voltage (HV) potential from the ohmic side. The AFP sensors present a 180 \( \mu \text{m} \) slim inactive edge on the side that faces the LHC beam.

The front-end electronics is the FE-I4B chip [7, 8] developed by the ATLAS collaboration for the IBL detector. 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. In the case of any discriminator being above threshold, the FE-I4B chip issues a fast signal through a dedicated HitOr pad. These signals are used to generate a trigger signal from AFP to ATLAS.

As already mentioned, the one-arm AFP system consists of two tracking stations placed in Roman Pots at 205 m and 217 m from the IP, that approach the beam horizontally. Each station is composed of four pixel modules arranged such that the short pixel direction of the sensor is horizontal to the LHC floor. Each module includes a 3D sensor interconnected to a single FE-I4B front-end chip, glued to a support holder and wire-bonded to a flexible printed circuit (referred to as flex). The modules are placed with a pitch of 9 mm and tilted by 14° with respect to the beam direction, to enhance hit reconstruction efficiency.
and horizontal position resolution (see figure 1).

![Figure 1. Design of the AFP detector including tracking and time of flight systems (left). The diffractive protons arrive from the left. The tracker modules mounted in the support frame (right). In this picture the slim edge side is facing up.](image)

3 Sensor Productions

The first CNM production of 3D sensors for AFP (run 6682), which started with 13 wafers, finished in July 2014. The fabrication mask set was identical to the IBL one. Each wafer included 8 3D sensors compatible with the FE-I4B chip. However, mainly due to damage at the wafer edge introduced during the DRIE process, 8 wafers broke during production. The remaining wafers were processed for under bump metalization at IZM (Germany) and diced at CNM with a standard diamond saw to 180 $\mu$m on the side facing the LHC beam.

The electrical quality of the sensors was determined through the measurement of the current-voltage (I-V) curves, which were obtained for each diced sensor using a probe station at room temperature. The n-side of the sensor was placed in contact with the grounded chuck via the under bump metallization, while the p-side was connected to the bias potential. This procedure does not ensure that all pixels are correctly biased (due to irregularities in the bumps, dust deposited in the chuck, sensor bow, etc), and a better method, explained below, was implemented in a successive sensor production. Given that the IBL 3D sensors showed excellent hit reconstruction efficiency even at low voltages [4], the sensors were classified as green (best quality) and yellow (medium quality) if the leakage current was below 10 $\mu$A at 20 V and 10 V respectively. The rest of the sensors were classified as red. The first production resulted in only 9 (5) green (yellow) sensors. Follow-up studies performed with a scanning electron microscope indicated that during the etching process damage was introduced to the column sidewall, which could partially explain the poor sensor yield. The low number of green sensors implied that problems that might result in the loss of sensors during the module assembly process (from bump-bonding to module testing) had to be minimized in order to produce enough tracking devices for the one-arm installation.

In order to test if the poor electrical performance of the sensors could also be related to an excessive p-stop implantation, several sensors with low breakdown voltage were irradiated
Table 1. Yield of the first and second sensor productions for AFP. After the fabrication process was optimized, a substantial improvement in both wafer and sensor yields was achieved.

| Production run | Wafer yield | Good wafers | Sensor yield | Good sensors |
|----------------|-------------|-------------|--------------|--------------|
| AFP 1 (6682)   | 38%         | 5           | 23%          | 9            |
| AFP 2 (7945)   | 83%         | 10          | 85%          | 68           |

at the TRIGA reactor at JSI Ljubljana with neutrons to fluences of 1, 10 and $10^{12}$ $n_{eq}/cm^2$ and annealed for a week at room temperature. The intention was to investigate if acceptor removal reduced the electric field in the area of the p-stops. Three of the 7 red sensors that were irradiated to $1 \times 10^{14}$ $n_{eq}/cm^2$ showed a clear improvement in the electrical behaviour, with a break down voltage ($V_{bd}$) that increased from a few volts to 20-35 V. One of these sensors was eventually mounted and installed in AFP (see next section).

Due to the low yield of the first AFP sensor production, CNM launched a second run (7945) after improving the fabrication process. The edges of the wafers were protected during the DRIE and the process parameters were optimized to reduce damage to the column sidewall. To refine the sensor selection process, the second production included a temporary metal layer that connected all the pixels. In combination with the pad of the 3D guard ring, the metal layer allowed an accurate determination of the I-V curve. The layer was removed before dicing by chemical etching. The second production finished in March 2016, with a distinctly improved yield: only 2 of the 12 wafers were lost during fabrication, while 68 of the 80 remaining sensors were of green quality. Table 1 summarizes the yields of the two AFP production runs while figure 2 compares the break down voltages.

![Figure 2. Break down voltage of 3D sensors from the first and second AFP productions.](image)

4 Module construction and quality assurance

The module production for the one-arm AFP detector needed to achieve an excellent yield, given the limited number of good sensors available from the first sensor production. In order
to avoid mistakes that could affect several modules, the assembly process was serialized, with at most two modules being mounted at the same time. The fact that all the assembly process steps, from hybridization (connection between sensor and readout electronics) to quality assurance (QA), were done in-house at IFAE, ensured that even this approach was relatively fast. The typical assembly time was 2–3 days per module.

To gain experience with the assembly process, low quality sensors were selected for the first modules, while the best ones were processed last. Bump-bonding was performed by IFAE with a Süss Microtech FC-150 flip-chip bonder machine with a reflow arm. During the bonding cycle the FE-I4B chips (with SnAg solder bumps) and the sensors were aligned, heated to 260 °C for a short period (about a minute) and pressed together lightly. In order to reduce the number of unconnected bumps due to bowing during the hybridization process, the thickness of the chips was kept at 700 µm (original wafer thickness). After flip-chip, the assemblies were processed in a fluxless formic acid reflow oven.

The bare assemblies were inspected with a high resolution (sub-micron) X-ray machine to discard devices with a large number of disconnected bumps. During the full production, 24 sensors of run 6682 were bump-bonded, though many of these devices were used to improve the assembly process. Only one device presented an area of disconnected pixels. The shape of this area indicated that the FE-I4B bumps were probably damaged during handling prior to the hybridization cycle. The I-V curves of the bare assemblies were measured with a probe station before the modules were fully mounted. Good correlation with the sensor pre-assembly measurements from the probe station was found.

The bare assemblies were glued to aluminium-carbon fiber carrier cards, designed by SUNY at Stony Brook and produced at Novapack. A combination of double sided Tesa tape and Araldite 2011 glue was used, the later being a radiation hard glue, already used in ATLAS for the IBL detector. The placement of the bare assemblies on the carrier cards was done with a pick-and-place machine using two alignment marks located in the cards. However, the distance between the assembly edge and the alignment marks in the long pixel direction was 2300 µm, which prevented an optimal alignment of the assembly. Furthermore, the 1 mm thick cards were found to present a ≈100 µm bow caused by the thinning to 0.5 mm of the region of the card where the FE-I4B chip is placed. This bowing hampered the correct placing of the modules during the placing step. The effect was reduced by increasing the thickness of the layer of tape. The final modules achieved an average placement precision of about 10 (30) µm in the short (long) pixel direction.

The flex circuit, designed by the University of Oslo, was glued to the card and the module production completed by wire-bonding. Long wires (≈ 2 cm) connected the HV pad of the flex to the sensor passivation opening on the p-side. The wirebonding quality was checked with wire-pull tests which indicated that 8-11 g were needed to break the bonds. The bonds broke at the heel during these tests.

The assembled modules were tested with the USBpix [9] and the HSIO-II [10] readout systems. The devices were tuned to a threshold of 2 ke− and a ToT of 10 (in units of 25 ns clock cycles) at an injected charge of 20 ke−, which corresponds to the values later used during the detector operation periods in 2016. The calibration was performed through the internal charge-injection mechanism of the FE-I4B chip. The calibration parameters that
control the injection (injection capacitance, slope of the transfer function of the injection voltage DAC and reference current setting) of each chip was previously determined at wafer level. The noise level of each assembly was extracted during the threshold calibration procedure. After calibration, tests with an external source were performed to verify charge collection and the connectivity of the front-end chip to the sensor. As already mentioned, only one device showed a significant number of disconnected bumps (>1%).

In order to check the mechanical stability of the assembly process, a module was subjected to an environmental stress test of multiple one hour thermal cycles from $-20^\circ$C to $40^\circ$C during one full day. The module was not operated during the cycles. Afterwards, the threshold and ToT calibrations, and the noise level, were compared with the initial results. No variations were found. Furthermore, no mechanical degradation was identified during an optical inspection. At a later stage, further thermal cycle tests were performed with four modules assembled for the second AFP arm. No electrical nor mechanical degradation was observed.

In total 17 modules, presented in table 2, were fully assembled. Two devices did not pass the QA procedure, since the communication with the front-end could not be established. Most of the other modules showed good performance with noise levels compatible with IBL modules. Module M01, with a sensor of very poor quality, and module M17 which presented a floating guard ring (the bumps that connect the guard ring to ground were removed before bump-bonding), showed a significantly higher noise. The overall assembly yield (including bump-bonding) was of 82% (14/17).

5 AFP tracker integration and operation

At the time of the one-arm AFP detector assembly at CERN, 4 tracker modules with green sensors were available, but since one had disconnected bumps, 3 of them were selected for installation. Another 3 yellow modules and a sensor which was pre-irradiated were also selected. The seven modules were shipped to CERN and fully re-tested prior to installation in the LHC tunnel in February 2016. During the initial testing of the system, it became apparent that the HV line of one module was shorted. This module was operated at 0 V. The one-arm tracker consists of three modules in the near station and four, but one without HV, in the far station. The detector temperature varies between $-5^\circ$C and $0^\circ$C depending on operation conditions.

The LHC accelerator ramp-up period (April-May 2016) allowed to integrate AFP with the ATLAS DAQ system. During the one bunch crossing LHC operation mode, AFP was timed-in with respect to ATLAS, ensuring that the AFP readout was within the ATLAS latency. LHC configurations with low number of bunch crossings were also used to study the positioning procedure of the Roman Pot system.

The AFP tracker was fully commissioned [11] in the first half of 2016 and diffractive events collected during dedicated low luminosity runs in August and October. Multiple high luminosity runs were also carried out through the year. Valuable experience in detector operation, performance and the interaction of AFP with other ATLAS sub-detector systems was collected during these runs.
Table 2. Summary of the AFP tracker module production. The sensor quality before and after irradiation is shown for pre-irradiated sensors. For two modules the communication with the front-end could not be established. Module M10 was operated at 0 V due to a shorted HV line. Modules M01 to M11 were mounted at the time of one-arm tracker assembly at CERN.

| Module | Pre-irrad. (10^{12} n_{eq}/cm^2) | Sensor quality | Disconnected | Noise (e^-) | Installed | Operational Voltage (V) |
|--------|--------------------------------|----------------|--------------|-------------|-----------|------------------------|
| M01    | No                              | red            | No           | 320±37      | No        | —                      |
| M02    | No                              | red            | —            | No comm.    | No        | —                      |
| M03    | No                              | yellow         | No           | 202±18      | Far       | 10                     |
| M04    | 100                             | red/green      | No           | 163±11      | Far       | 30                     |
| M05    | No                              | yellow         | No           | 162±11      | Near      | 5                      |
| M06    | No                              | yellow         | No           | 160±10      | Near      | 10                     |
| M07    | No                              | green          | 15%          | 154±13      | No        | —                      |
| M08    | No                              | green          | No           | 160±11      | Near      | 10                     |
| M09    | No                              | green          | No           | No comm.    | No        | —                      |
| M10    | No                              | green          | No           | 156±11      | Far       | 0                      |
| M11    | No                              | green          | No           | 166±11      | Far       | 5                      |
| M12    | No                              | green          | No           | 169±11      | No        | —                      |
| M13    | No                              | green          | No           | 171±11      | No        | —                      |
| M14    | No                              | green          | No           | 165±11      | No        | —                      |
| M15    | No                              | green          | No           | 175±11      | No        | —                      |
| M16    | 10                              | red/green      | No           | 175±12      | No        | —                      |
| M17    | No                              | green          | No           | 262±20      | No        | —                      |

6 Conclusions and outlook

AFP aims to extend the physics reach of ATLAS by identifying events with one or two intact protons scattered in the forward direction. The one-arm AFP detector includes a tracking system with 3D pixel sensors. The first sensor production at CNM suffered from low yield. However, due to the excellent turnout of the module assembly process, seven tracker planes were installed in two Roman Pot stations on one side of the ATLAS IP in the LHC shutdown of 2015-2016. The detector successfully collected LHC proton-proton collision data during dedicated runs in 2016.

After the sensor production process was optimized, the recently completed second sensor production showed a significantly improved yield. New tracker modules are being assembled for the full two-arm AFP detector that will also include the ToF system and which is foreseen to be installed in the shutdown of 2016-2017.

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References

[1] ATLAS Collaboration, Technical Design Report for the ATLAS Forward Proton Detector, Tech. Rep. CERN-LHCC-2015-009. ATLAS-TDR-024, CERN, Geneva, May, 2015.

[2] ATLAS Collaboration, The ATLAS Experiment at the CERN Large Hadron Collider, JINST 3 (2008) S08003.

[3] J. Lange, E. Cavallaro, S. Grinstein, and I. Lopez Paz, 3D silicon pixel detectors for the ATLAS Forward Physics experiment, JINST 10 (2015) C03031.

[4] J. Lange, et al., Beam tests of an integrated prototype of the ATLAS Forward Proton detector, JINST, 11 (2016) P09005.

[5] ATLAS Collaboration, ATLAS Insertable B-Layer Technical Design Report, Tech. Rep. CERN-LHCC-2010-013. ATLAS-TDR-19, CERN, Geneva, September, 2010.

[6] G. Pellegrini et al., 3D double sided detector fabrication at IMB-CNM, Nucl. Instrum. Meth. A 699 (2013) 27.

[7] V. Zivkovic, et al., The FE-I4 pixel readout system-on-chip resubmission for the insertable B-Layer project, JINST, 7 (2012), C02050.

[8] M. Garcia-Sciveres et al., The FE-I4 pixel readout integrated circuit, Nucl. Instrum. Meth. A 636 (2011) S155.

[9] M. Backhaus, et al., Development of a versatile and modular test system for ATLAS hybrid pixel detectors, Nucl. Instrum. Meth. A 650 (2011) 37.

[10] M. Wittgen et al., A Reconfigurable Cluster Element (RCE) DAQ Test Stand for the ATLAS Pixel Detector Upgrade, Topical Workshop on Electronics for Particle Physics (TWEPP), Aachen, Germany, September 2010.

[11] I. Lopez Paz, The AFP Silicon Tracker, 3rd Elba Workshop on Forward Physics @ LHC Energy, Elba, Italy, May 2016.