The front-end hybrid for the ATLAS HL-LHC silicon strip tracker

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ABSTRACT: For the HL-LHC, ATLAS [1] will install a new all-silicon tracking system. The strip part will be comprised of five barrel layers and seven end cap disks on each side. The detectors will be connected to highly integrated, low mass front-end electronic hybrids with custom-made ASICs in 130nm CMOS technology. The hybrids will be flexible four layer copper polyimide constructions. They will be designed and populated at the universities involved, while the flexible PCBs will be produced in industry. This paper describes the evolution of hybrid designs for the barrel and end cap, discusses their electrical performance, and presents results from prototype modules made with the hybrids.

KEYWORDS: Front-end electronics for detector readout; Electronic detector readout concepts (solid-state); Particle tracking detectors (Solid-state detectors); Si microstrip and pad detectors

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1 Introduction

The next step for the Large Hadron Collider will be a High Luminosity Upgrade, referred to as the HL-LHC project [3]. The upgrade to a more powerful accelerator complex will be accomplished in two phases. In phase 2 the ATLAS experiment will replace the current inner detector with an all-silicon tracking system in order to cope with the increased demands. This implies the replacement of the Transition Radiation Tracker (TRT) with a silicon strip tracking system. A sketch of the cross sectional view of the proposed overall inner tracker layout, composed of silicon pixel and strip detectors, is depicted in figure 1.

By the start of phase 2, after an integrated luminosity of about $700\text{fb}^{-1}$, a completely new inner detector will be needed regardless of the LHC upgrade plans, due to the significant radiation damage and additionally due to accumulated on-detector faults which impact on physics performance of the detector. An improved radiation resistant and more granular detector structure will be required for the $10\times$ higher instantaneous luminosity, and the much higher track density, after the upgrade. The inner tracker system has to withstand increased particle fluences. In order not to have a negative impact on the physics reach of the detector, low mass and low radiation length materials are required. To keep the costs at a reasonable level, new n-in-p technology has been adopted for the inner tracker silicon strip sensors.

The silicon strip part of the inner tracker is electro-mechanically partitioned into central and forward regions. As shown in figure 1, the central region will be comprised of five full length barrel layers (two short strip, three long strip layers) plus one stub layer (to compensate for the loss in the transition region) whereas, the forward region will be comprised of seven end cap disks on each side (shorter strips in the vicinity of the beam line and longer strips in higher radii). For details, consult [4, 5].

2 Baseline designs

In this section, a general overview is given of the baseline concepts of the central and forward regions of the inner strip tracker. The front end electronics to readout the strip detectors will be 130nm technology custom designed mixed signal ASICs (the ABC130) mounted on low mass,
polyimide based multilayer flexible PCBs. These highly integrated hybrids are mounted directly on silicon sensors. Mechanically, the hybrids are glued directly to the surface of the sensors. All electrical connections to the sensors and to the ASICs are through bonding wires. These electrical structures, referred to as single-sided modules, are the basic electrical building blocks of the system. Hybrid assembly, ASIC mounting, wire bonding and module building are all performed in-house either with automated machines or with custom designed and fabricated mechanical tools.

The available wafer size (currently 6”) used to fabricate the silicon strip sensors along with the geometry of each inner tracker region, dictates the adopted segmentation of the sensors. The occupancy is then kept at a desirable level by subdividing the sensors in several strip rows [4]. Strips are in general shorter, closer to the beam pipe and longer, farther away.

2.1 Barrel

The baseline concept in the barrel is the Stave [6]. It is a highly integrated, modular structure, consisting of single-sided modules mounted on two sides of a mechanical core structure, with a total length of 1.4m. The barrel modules are in turn composed of silicon strip sensors with a number of hybrid flex circuits mounted on them. Figure 2 depicts sketches of a short strip stave, illustrating also its cross section and a single-sided module. A total of 13 single-sided modules are mounted on each side of a stave. They are glued onto flexible copper-polyimide based bus tapes laminated on either side of a low mass, carbon fiber based core structure with embedded titanium cooling pipes. Barrel modules are envisioned to be identical with stereo angle between the two side made by rotating the modules of one side by 40mrad. Staves are tilted at 10° in phi relative to the barrel support structure to minimize Lorenz angle effects.

The axial strips of the barrel sensors on the two sides of the stave construct small angle (40mrad) stereo pairs. All modules are otherwise identical. The staves are mounted 10° tilted on barrel mechanical support structures.

Each short strip barrel sensor is approximately 10 × 10cm², as shown in figure 2, the sensors consist of 1280 short strips, each with an approximate strip length of 2.5cm. The new readout front end ASICs (130nm based technology chips) are designed to read out two adjacent rows of 128 strips each. Consequently, a total of 20 ABC130 chips, arranged in two rows of 10 ASICs each, are required to readout a short strip barrel sensor. The ABC130 chips are integrated on a
polyimide based multi-layer flexible PCBs (hybrids). Each barrel hybrid serves 10 ABC130 chips along with other passive components and an additional ASIC (the Hybrid Control Chip, HCC\textsuperscript{1}). Two hybrids will then readout each short strip barrel sensor. The powering of the hybrids and high voltage biasing of the sensors through off-hybrid circuitry are currently subject of intensive R&D. The first thermo-mechanical prototype hybrids have already been designed and fabricated, which allow for the investigation of the thermal characteristics of the module and mechanical assembly and wire bonding trials. Figure 3 shows a manufactured ABC130 hybrid. The expected power dissipation of the new generation barrel hybrids is about 2W with the sensors adding about 1W at the end of operations. This results in an approximate overall power dissipation of a single-sided short strip barrel module of about 5W. The layer build up is similar to the electrical versions, which are currently being designed. Here several module powering and readout issues, along with the new features implemented into the new generation of ABC130 front end ASICs, will be addressed and evaluated. The ABC130 hybrids have the same width of the sensors and are mounted with no overhang on the sensors. The new hybrids are also narrower and thinner than the hybrids using ABCN250 ASICs. This is to done to reduce material as much as possible. Although same industry standard design rules have been adopted, the routing is more demanding than previous versions as higher clock and data rates are planned for the readout and several new features and algorithms have been added to the ABC130 and HCC.

\textsuperscript{1}HCC: Hybrid Control Chip, is essentially an on hybrid readout bridge, 130nm CMOS process, ASIC. The chip is currently under development.
The hybrids are highly integrated entities, with a large impact on the overall performance of the system. Several barrel hybrids, based on the predecessor 250nm CMOS technology front end readout ABCN-25 ASICs [2], have been prototyped so far. These have been tested quite thoroughly, themselves being the test platform for evaluating other features of the readout front end ASICs, the noise performance of the sensors and powering of the system. An example of a fully populated, early generation ABCN-25 barrel hybrid and its flex circuit layer build up is shown in figure 4. Various hybrids, with and without shield layer, have been fabricated and tested. Solid ground layer is on the bottom, followed by power, signal traces and finally components on the top. The adopted design rules are the industry standard of 100µm track and gap width ≥ 350µm/150µm pad/drill vias. These hybrids are 108mm long by 24mm wide. The electrical and functional tests of hybrids have been quite successful with a typical average noise figure of ABCN-25 ASICs of about ≤ 400 e\(^{-}\), comparable to single chips.

Figure 5 shows a built, single-sided short strip 250nm barrel module and a module in a test frame. The position of the ASICs is centered to the sensor strip with all connections being via wire bonds. These electrical modules are the building blocks of reduced sized prototype substructures called Stavelets [7]. Stavelets were constructed to investigate various powering and signaling scenarios. Modules are placed on a jig with integrated cooling pipes. Hybrids are cooled through the sensors, which are in turn cooled down by the jig. Many successful intensive studies have been conducted with noise figures less than 650 e\(^{-}\).

2.2 End cap

The end cap disks are mechanically subdivided in wedge shaped structures called Petal, as illustrated in figure 6. The Petal concept is quite similar to that of the stave. Mechanically the Petal core is constructed quite similar to the stave core. Each end cap disk has six radial partitioning, referred to as rings. The three outer rings are additionally partitioned in azimuth. In order to minimize occupancy the inner rings sensors have short strips, whereas the outer rings have long strips. A total of nine sensors are mounted on each side of a Petal. The sensors are segmented in short/long strips (inner/outer rings). Each of the nine end cap sensors is different, with differing strip pitch both on each segment of a given sensor and on different sensors. As a consequence, there will be
Figure 5. Right: a built physical single-sided 250nm barrel short strip module. Left: such a module in a test frame, mounted on a test jig with integrated cooling pipes.

Figure 6. Left: sketch of a double sided end cap Petal. Right: schematic illustration of one end cap showing the mechanical support structure and the concept of Petal.

up to 13 different end cap hybrids with different number of front end readout ASICs. The sensor strips have a small stereo angle (20mrad) built in. Various options are being prototyped and tested to aid decision taking in near future. For details on these and related topics refer to [10].

The geometrical diversity of the end cap sensors, especially in some critical regions, makes the hybrid design a complex task. The innermost ring has both fine pitch and very short strips. The upper rings have additionally split sensors in azimuth (φ). For these reasons a mini Petal prototype (called Petalet) is being built to evaluate various options and solutions for those two regions. Mini sensors with proper geometries (as shown in figure 7) have been fabricated by CNM [9] for the Petalet program. These sensors have been used to build Petalet modules. Modules are then tested individually and mounted on the bus tape glued to the surface of the Petalet core structure. An important goal of the Petalet program is to investigate different powering and readout options along with other specific issues.

The Petalet project studies two basic architectures of power and data/control signal connections to the hybrids. One option has all connections on a common side (called common power);
whereas, the other splits these and puts power and signals on opposite sides (called split power). The complexity of either design of the hybrid or system design and their integration aspects will then be extrapolated from these studies to the Petal proper. From these studies one option will be selected for implementation. Each option has implications on the bus tape design, on the readout and powering.

Petalet hybrids have already been designed and manufactured, and populated in-house. The layer stack-up along with pictures of the bare and the fully stuffed hybrids of the options are shown on figures 8 and 9, respectively. Although the layer stack-ups differ, the design rules are, as in the barrel case, industry standard. Different approaches of differential signaling have been adopted with microstrip used as opposed to stripline. Electrical and functional tests have been very promising with similar noise figures to the barrel hybrids, as shown in figure 10. In this figure, a test frame for the common power hybrids is also shown. Petalet modules (shown in figure 7 for the split power case) have also been tested extensively with noise figures as expected of about 650 ENC.
Figure 9. The picture of two (left & right) bare and fully stuffed common-power-option ABCN-25 hybrids along with a diagram of the hybrid build.

Figure 10. Left: hybrid test frame for the common power option of the Petalet, showing a fully populated hybrid and daughter boards. Right: example noise plot obtained during tests.

3 Conclusions

The design, fabrication, assembly and testing of various prototype hybrids for the ATLAS Upgrade silicon strip tracker have progressed greatly during the last years. The barrel Stave/Stavelet programs are quite mature; whereas, the end cap, due mainly to the complexity of the sensor layout, has only recently started with the Petalet project. The hybrids of the Stave/Stavelet and Petalet programs are highly integrated, Cu-Polyimide based, multi-layer flexible PCBs housing multiple 130nm (or 250nm) CMOS technology ABCN front end readout ASICs. The fabrication of the hybrids has been done in three different European companies with comparable qualities and test results. There are still challenges to face with the new 130nm CMOS process readout chip-set (ABC130 + HCC), which have higher clock/data rates, extra features and complexity. Power and signal integrity will be major topics of investigations, along with system integration and mechanical challenges.
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