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Production of flex circuits for the ATLAS Inner Tracker Pixel Outer Barrel

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Abstract: The ATLAS ITk Pixel system requires large-scale flex circuits for low-voltage power, high-voltage sensor bias, and command/data transmission due to tight space constraints. This reports will focus on the design and production of the services that runs from the modules and the first patch panel of the ITk Pixel Outer Barrel. The results from the quality control tests on the pre-production (10% of what is needed to equip the final detector) will be discussed. In this report we also describe the procedure developed for the complex 3D bending needed to accommodate the routing and to respect the mechanical envelope.

Keywords: Special cables, Manufacturing

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Introduction

The Large Hadron Collider (LHC) will go through a major upgrade to increase its instantaneous luminosity by a factor of ten. The High Luminosity phase of LHC (HL-LHC) is planned to start in 2030 and, consequently, the ATLAS experiment [1] is going to replace its inner detector with the Inner Tracker (ITk) [2, 3], a new silicon tracker that can cope with the harsher HL-LHC environment.

In the ITk Pixel detector, the on-detector, a.k.a. type-0, services are all the electrical links from the modules to the first patch panel (PP0) for powering, data, clock/command and detector control system (DCS). They are located on the detector itself, physically attached to the outer barrel mechanical structures. This report focuses on the design, production and quality control of the on-detector services for the ATLAS ITk Pixel Outer Barrel sub-system. In particular, Section 1 deals with the description of the on-detector services: their specifications, electrical outlines, and bending procedure are presented. Section 2 is than dedicated to the quality control of the pre-production, accounting for 10% of what will ultimately be produced for ITk.

1 On-detector services for ITk Pixel Outer Barrel

Figure 1 gives an overview of the on-detector services for the ATLAS ITk Pixel Outer Barrel. The PP0 connects the services that runs out of the detector volume on one side and links the modules on the other side. The PP0 is made of a flex-rigid PCB to route and distribute all the signals up to individual flexible wings. There are two versions for the flat part described in this document: the short one called M6 and the long one called M12, serving 6 and 12 modules, respectively. Each PP0 is equipped with a Monitoring of Pixel System (MOPS) chip. The pigtail is the link between the PP0 wing and the module. Several flavors are needed to be adapted to different regions of the detector. It is based on a multi-flex PCB technology and it requires a complex 3D bending to accommodate the routing while respecting the mechanical envelope.

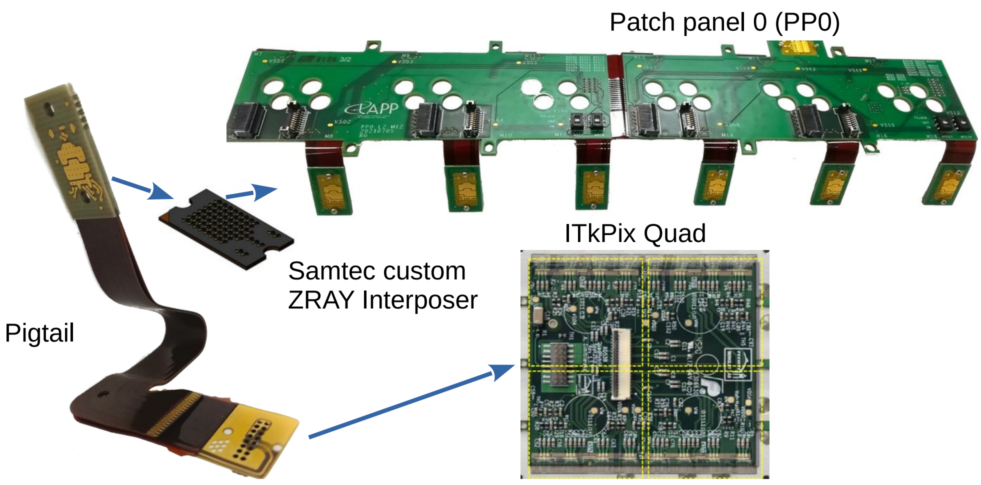

Figure 1. Overview of the on-detector services for the ATLAS ITk Pixel Outer Barrel.

1.1 Specifications and design principles

Several requirements were imposed on the design of on-detector services to guarantee the proper functioning of the detector.

First of all, in order to achieve the best possible physics performance the inert material of the detector has to be minimized, therefore the thickness of all copper layers had to be minimized. On the other hand, the powering of the ITkPix front-end chips requires a current of 6 A and the physical constraint on maximal heat dissipation translates into a resistive budget of 400 mΩ for an M6+M12 service chain.

The desired data transmission speed of 1.28 Gbps requires a good control over the impedance of data differential pairs, namely $100 \pm 10\Omega$. Additionally the transmission loss for each lane from the module to the opto-transceiver is required to be better than −20 dB.

As far as the high voltage is concerned, it is expected that at its end of life ITk will be operated at 850 V, therefore two kind of specifications were set for the design of the high voltage (HV) part of on-detector services: leakage current at 850 V below 100 nA and a dielectric breakdown voltage greater than 1.2 kV.

From the mechanical point of view, a precise envelope around the module required flex PCBs to be routed with a precision of 100 µm in the most critical parts close to wire bonds.

In order to withstand the required radiation dose of 250 MRad and for safety in case of fire, only halogen-free materials were used.

1.2 Electrical outlines and stack-up

Two pigtail and two PP0 outlines have to be produced to equip the central part of the ITk Pixel outer barrel, with mechanical differences among the three layers that can be taken care of with different bending angles.

Two manufacturers were ultimately chosen for the production of on-detector services, namely CERN and TechCI. The production flow of the two manufacturers are very similar to each other and in case of problems for one manufacturer it is possible to ask the other to take over. In particular, to be consistent with the resistive budget, a non standard thickness of 55 µm for the copper layers of the pigtails had to be used.

As far as the ZRay interposer is concerned, this is also a custom object. The ZRay interposer is part of a contact matrix connector, but few pins had to be removed to increase the clearance around the HV pins and hence increase the dielectric breakdown voltage. Additionally, it is halogen-free.

The left side of figure 2 shows the outline of pigtails for the central part of the ITk Pixel outer barrel. A close-up of the ZRay connector showing the missing pins is displayed on the right side.

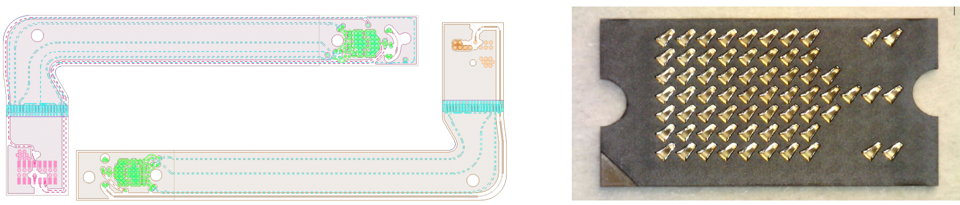

Figure 2. Left - outline of pigtails to be used in the central part of the ITk Pixel outer barrel. Right - Close up a custom ZRay interposer. Missing pins to increase HV clearence can be noticed.

1.3 Bending procedure

The precise envelope for the flex PCB required lot of prototypes to tune the bending procedure. Special molds had to be designed and experience showed that the pigtails inside the mold had to be warmed up to 120 °C for one hour in order for the shape to be fixed. Figure 3 shows the pigtail bending tools: on the left side, the pigtail is in the mold, whereas on the right side the mold is open and the resulting bents on the pigtail can be sees.

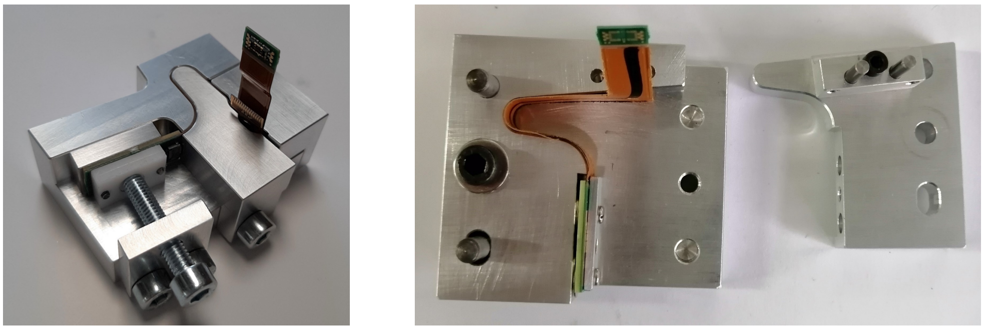

Figure 3. Photos of pigtails bending tools. Left - pigtail in the mold. Right - Open mold with shaped pigtail at the end of the bending process.

2 Quality control tests

With the prototyping phase over, 10% of the total amount of pigtails and PP0s were produced for each flavor. In this section the quality control tests performed to check if the objects are consistent with the specifications are discussed.

2.1 3D scan of bent pigtails

First of all, it was checked if the bending procedure is under control, meaning that the bent PP0s and pigtails are inside the assigned envelop. The most stringent mechanical constraints are on the pigtails, so for the sake of simplicity, this report will only focus on them. Figure 4 shows the 3D scan of a pigtail with its connector fixed at their nominal positions. The color map represents the difference with respect to the the nominal CAD model. Differences of no more than 500 µm are observed with a maximum of 100 µm in the most critical area, therefore within the assigned envelope.

2.2 Resistance budget

The resistance of the full serial powering chain was measured with a four-wires method. The measured quantity includes: the connection to the PP0, the PP0, and all the pigtails with the ZRay connectors. At the module side, custom PCBs with negligible resistance are used to short the serial powering chain. For the M6(12) PP0 + pigtails a value of 135(185) mΩ is measured, hence an overall short + long chain resistance value of 320 mΩ well below the required value of 400 mΩ.

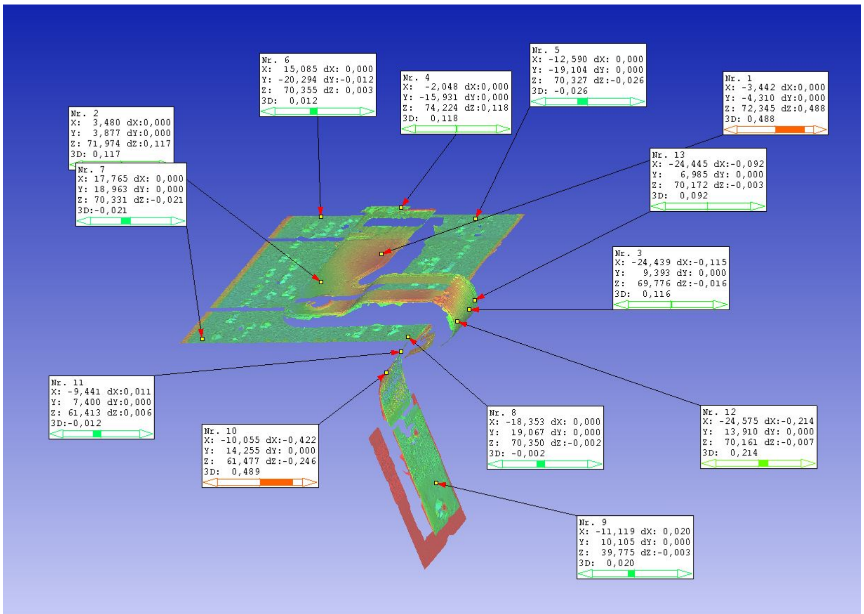

Figure 4. 3D scan of a bent pigtail. The color map gives the difference with respect to the the nominal CAD model. Differences of maximum 100 µm in the most critical area are observed.

2.3 Temperature homogeneity

The temperature of a PP0 with pigtails was photographed with a thermal camera for serial poweing chain currents between 1 A and 8 A. The device under test (DUT) was set on a test bench with no cooling except for air convection. The air temperature in the room was 22 °C. Figure 5 shows the thermal photos for currents of 4 A, 6 A, and 8 A, from left to right. At the nominal current value of 6 A the temperature increase is 15 °C with the hot spot on the ZRay connector area, as expected. The temperature homogeneity on the full surface of both rigid and flex parts indicates a good homogeneity of the PCB manufacturing.

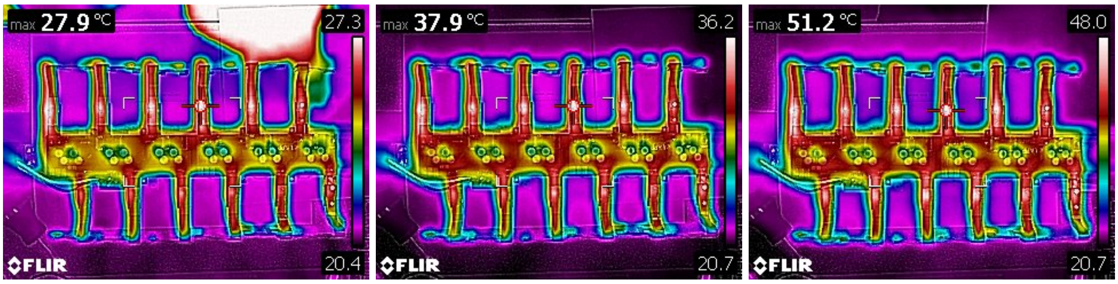

Figure 5. From left to right, temperature maps of an M12 PP0 and pigtails with a current of 4 A, 6 A, and 8 A through the serial powering chain.

2.4 High voltage tests

The leakage current at the expected end-of-life operation voltage of 850 V was measured for 10 M6 PP0s and 5 M12 PP0s. The high voltage was applied to the PP0s with pigtails disconnected at the module side. After 1 min the leakage current was measured and found to be at most 5(7) nA for M6(M12) PP0s, therefore well below the required 100 nA.

Additionally, the dielectrics breakdown voltage was also checked on one M6(M12) PP0 and found to be 1.65(180) kV. The specification of at least 1.2 kV is then also respected.

2.5 Transmission loss

The transmission loss (s_{21}) of all differential data and command pairs on a PP0 + pigtail was measured. Figure 6 shows the results as a function of the frequency. In particular at 640 MHz an average (maximum) loss of −1.5(−1.8)dB is measured. Such value has to be compared to the specification of −20 dB for the whole service chain up to the optical transceivers. The cross-talk among data pairs was found to be negligible (better than −50 dB).

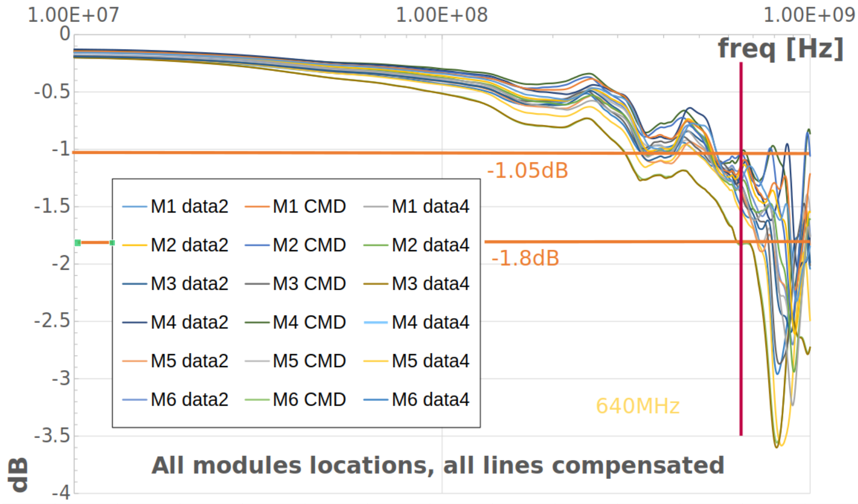

Figure 6. Transmission loss as a function of frequency on all data and command pairs of a PP0 + pigtail.

2.6 Yields

Overall, 260 pigtails for each flavor were tested and only one bad pigtail was found. Manufacturers test each pigtail and PP0, then they ship only good ones and do not disclose the number of items they rejected, therefore a complete yield calculation is not possible. From this data it is possible to conclude that cabling and bending have a yield greater than 99.5%.

3 Conclusions

The design and production of on-detector services of the ITk Pixel Outer Barrel was presented. The tests on the pre-production show good agreement with the specifications with a yield greater than 99.5%. The complex procedure of 3D bending is well under control as shown by metrology measurements. All is ready for the production phase starting at the beginning of 2025.

Acknowledgments

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References

[1] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, 2008 JINST 3 S08003 [doi:10.1088/1748-0221/3/08/S08003]

[2] ATLAS Collaboration, *Technical Design Report for the ATLAS Inner Tracker Strip Detector*, CERN-LHCC-2017-005 [cds:2257755].

[3] ATLAS Collaboration, *Technical Design Report for the ATLAS Inner Tracker Pixel Detector*, CERN-LHCC-2017-021 [cds:2285585].