ATL-ITK-PROC-2024-044
01 November 2024

Prepared for submission to JINST

Design production and testing of ATLAS ITk strip bus tapes

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Abstract: This paper reviews the bus tapes used for the barrel and end cap detectors for the ATLAS ITk strip detector. The long cooper/polyimide tapes with narrow track and gap are very challenging to produce with an acceptable yield. Two different technologies for these tapes are compared. After several iterations, barrel and end cap tapes are in production at two different manufacturers. Results form the electrical and dimensional QC show that both approaches meet the tight specifications. Tests of the radiation tolerance are also discussed.

Keywords: Particle tracking detectors (Solid-state detectors), Manufacturing, Radiation-hard detectors

1 Introduction

The ATLAS ITk strip detector has chosen a design in which all electrical and cooling services are integrated into a carbon fibre sandwich structure [1]. For a recent review of the full ITk detector, see [2]. All high speed signals, low voltage power and high voltage are supplied by a copper polyimide bus tape. The same concept with different geometries is used in the barrel and end cap regions.

The key requirements and challenges for the bus tapes are summarised in sections 2,3. The advantages and disadvantages of the two technologies used are reviewed in section 4. Some of the key electrical and dimension tests are discussed in section 5. The tests to validate the radiation tolerance are reviewed in section 6. A brief conclusion is given in section 7.

2 Requirements

The key requirements for these bus tapes are

- Distribution of 640 Mbps data from all modules on a stave or petal to an End of Sub-structure (EoS) card [3]. The EoS card provides all the optoelectronics for communication with the ATLAS off-detector electronics [1],
- Distribution of 160 Mbps control data from the EoS card to the modules. In order to minimise the number of lines on the tape, multi-drop transmission is used with up to 10 HCCStar [4] receivers.
- In order to minimise reflections for the high speed data transmission, the impedance of all differential pairs should be $Z_0 = 100 \pm 10\ \Omega$.
- The low voltage (11V) is distributed from the EoS to all modules. The round-trip voltage drop must be less than 1V (the voltage drop on the return line must be less than 0.2V).
- The high voltage (up to -550V) is distributed from the EoS card to all modules. Sufficient clearances must be maintained to avoid high voltage leakage currents.
- The tapes must survive radiation doses of 500 kGy(Si) and 650 kGy(Si) for the barrel and end cap tapes.
- The radiation length should be minimised. This is achieved using the highly integrated carbon fibre sandwich.

3 Challenges

Precise control of etching is required to achieve the required impedance. There are a large number (up to 44) of narrow (nominal 100 μm) track and gap lines. The tapes used in ATLAS must not have any open or short circuits, therefore it is particularly difficult to achieve a sufficiently high yield. Having good quality nickel/gold plated pads for wire bonding is difficult over large area tapes. The tight stretch requirement is challenging to maintain over the long production times. The distortion requirement required the development of custom tooling for the 1.4 m long narrow barrel tapes. The tapes must be sufficiently radiation tolerant for use at HL-LHC.

4 Technologies

The tapes use adhesiveless copper on 50 μm polyimide for optimal adhesion. The tapes have cover layers on the top and bottom sides. Two different approaches have been used for the barrel and end cap tapes to allow connection to the bond pads. For the barrel tapes, vias are used to connect the tracks on the bottom copper layer to the top copper layer. Therefore wire bonding is only required on the top copper layer. Mechanical milling is used to create the openings in the cover layer for the bond pads. This approach starts with a thin copper layer (2 μm) which is drilled before electroplating to the required thickness. For the end cap tapes, access to pads on the top and bottom copper layer are provided by laser ablation through the cover layer and base polyimide. Additional cleaning steps are required to achieve the cleanliness and required surface finish for the bond pads.

The advantages and disadvantages of the two approaches are summarised in Table 1.

Table 1. Comparison of two technologies for flexible tapes. Petal tapes are made by ELGOLINE [5] and barrel tapes by CERN

Laser Ablation (ELGOLINE)	Vias (CERN)
Special processing for copper pads before NiAu	Vias connect bottom Cu to top Cu.
Cleaning for plating for wire bonding	Only wire bond to top Cu.
isopropyl alcohol and MECBRITE CB5008 [6]	
plasma cleaning	
	Use large enough vias and have redundant vias
	Validated with destructive tests.
Laser cuts very precise openings in cover layer.	Mechanical milling results in less precise openings
	therefore larger openings are required.
Stretch sensitive to environmental parameters	Stretch constrained by milling holes for dowel pins
Cu thickness from material	Cu thickness from electroplating.
	Difficult to control for large area flex.

5 Test results

Some of the key electrical (dimensional) test results are reviewed in section 5.1 (section 5.2)

5.1 Electrical tests

Most of the electrical and all the dimensional QC is performed using custom Bus Tape Testing Robots (BTTR). Each BTTR have two cameras and probes mounted on independent x/y/z stages. The cameras take images of fiducials on the tapes and the measured position of the fiducials are compared to the ideal (CAD) positions. There are fiducials near each bond pad, which allows the BTTR to probe accurately on narrow bond pads even if the tape is distorted on a scale larger than the width of a bond pad. The BTTR measures resistance for all pads along each network and then looks for short circuits between neighbouring nets. Finally the BTTR measures leakage current between all pads used for high voltage distribution and neighbouring pads. The impedance of a test differential pair trace on each tape is measured with a TDR oscilloscope.

Fits are made to graphs of resistance versus length for all the narrow lines. The distribution of the fitted gradients for the nominally 100 μm wide lines for the barrel tapes is shown in figure 1 [7]. There is a considerable spread in the fitted slopes and this is explained by the spread in copper thickness (measured before etching), see figure 1 [7].

The distribution of measured impedance of the differential test traces for production barrel and end cap tapes is shown in figure 2 [7]. Both distributions are within the allowed range of $90 < Z_0 < 110\ \Omega$.

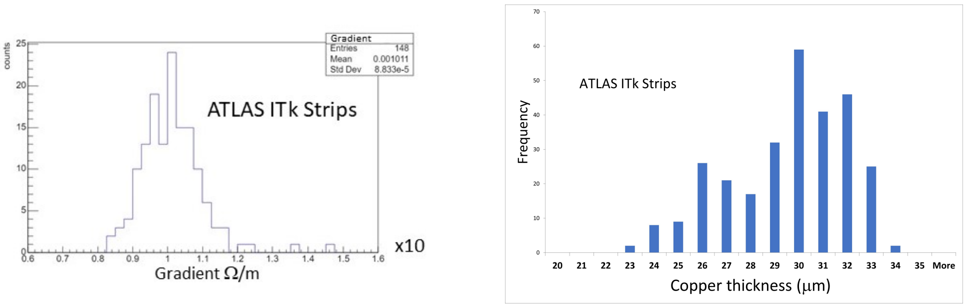

Figure 1. Distribution of fitted gradient of resistance versus distance (left) and distribution of copper thickness (right) for production (barrel) CERN tapes.

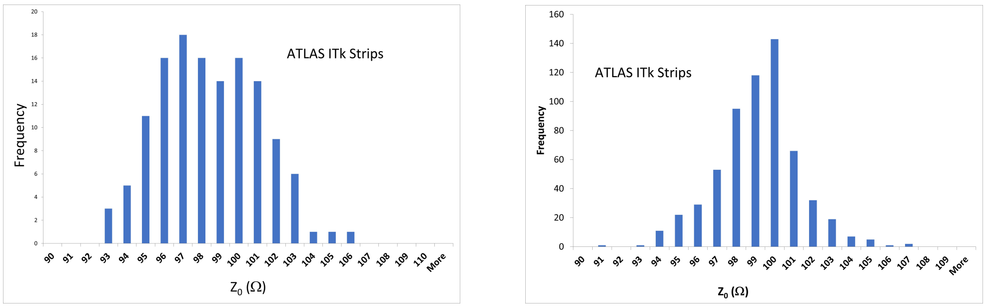

Figure 2. Distribution of impedance measured on a test trace for production barrel (left) and end cap tapes (right).

The quality of the nickel/gold plated pads for wire bonding is assessed with wire bond pull tests on test coupons. The mean pull test force versus serial number (proxy for time) is shown for end cap production tapes in figure 3 [7]. The variation of mean bond pull strength with surface roughness is shown in figure 3 [7]. This shows that to achieve acceptable bond pull force, the surface roughness should be less than 0.7 μm. For the long barrel tapes, it was very difficult to achieve uniform bond pull tests over the full area of the tape. Many trials were made and the most important improvement was to hold the tapes horizontal in the nickel plating bath, as this minimised the effect of the vertical variation in concentration of the plating solution. The final demonstration

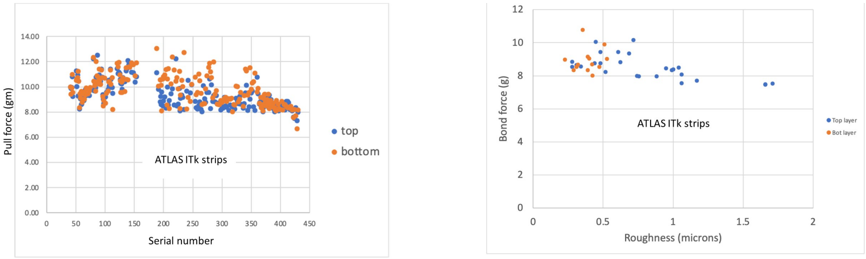

Figure 3. Measured mean bond pull test f_{pull} versus serial number (proxy for time) for petal tapes (left) and mean bond pull force versus surface roughness (right). The ATLAS requirement is $f_{pull} > 8$ gm.

of the electrical functionality of the bus tapes comes from operation on staves and petals loaded with modules. Example eye diagrams for the worst case location on barrel tapes for the point to point and multi-drop links are shown in figure 4 [7]. The 640 Mbps data shows the effect of dispersion but the eye-opening is still satisfactory. The eye-diagram for the multi-drop line shows the effect of reflections but again the eye-opening is still satisfactory.

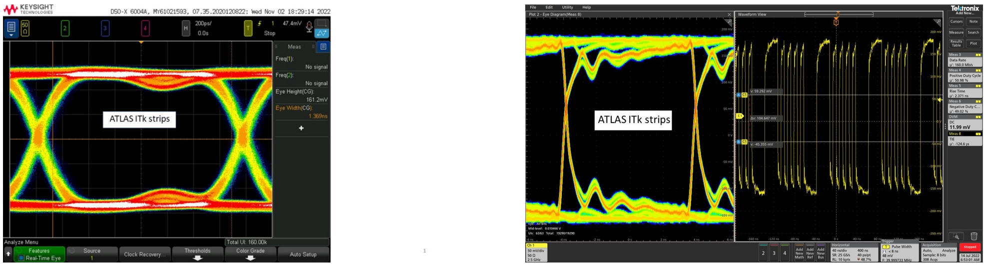

Figure 4. Eye diagrams for point to point data transmission at 640 Mbps for a 1.4 m long line (left) and for multi-drop line at 160 Mbps for the worst case of 10 HCCStar receivers (right).

5.2 Dimensional tests

The distribution of stretch measured on barrel tapes after co-cure is shown in figure 5 [7] and is well contained within the allowed limit of $|\text{stretch}| < 10^{-3}$. The stretch versus serial number (proxy for time) for the end cap tapes is shown in figure 5. The long term trends are corrected by changing the gerber files. It is essential to minimise distortion in the short direction of the tape in order to maintain suitable clearances for high voltage (see figure 6 [7]). For each fiducial on the tape the (x,y) location is measured with the BTTR. The distance in y from the fiducials to the centre line is calculated, y_i. The ideal value $y_{nominal}$ is calculated form the CAD data. For each fiducial $\Delta y_i = y_{\text{measured}} - y_{\text{nominal}}$ and the distortion is defined as $D = max(|\Delta y_i|$. Special tooling was used to control any distortion during the co-cure process. The distribution of D for barrel tapes is shown in figure 6 and is contained within the maximum allowed value of 0.6 mm.

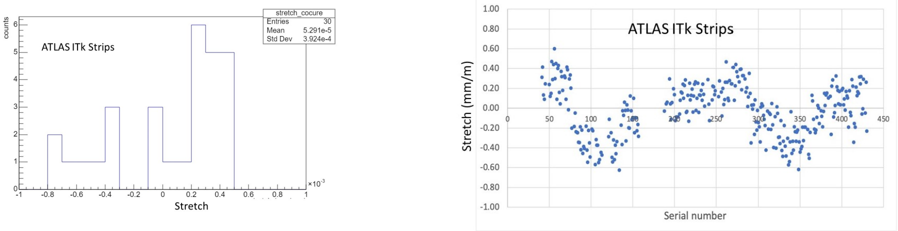

Figure 5. Distribution of stretch (dimensionless) for production barrel tapes (left). Stretch versus serial number (proxy for time) for petal tapes (right).

6 Radiation tolerance

The part of the bus tapes which are sensitive to radiation damage is the glue used to join the polyimide cover layer to the base copper/polyimide tape. The radiation tolerance is assessed by measuring the pull strength of test samples in a pull tester, for samples with and without radiation. A summary of one data set for test samples using the Apical and Krempel material which are used

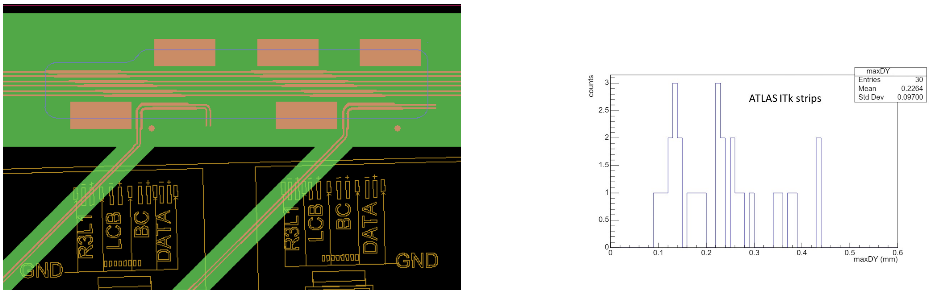

Figure 6. Detail of CAD layout for a barrel bus tape showing edge of silicon module (at high voltage) and exposed bond pads at low voltage (left). Measured distortion (see text for explanation) for production barrel bus tapes after co-cure (right).

for barrel tapes is given in Table 2. As the material is not specified as being radiation-tolerant it is essential to perform a batch test on each new roll of cover layer. Similar tests are made using the Kapton material used for the end cap tapes.

Tests were performed on samples using the Taiflex material which was being used by a potential industrial partner and revealed extremely poor radiation tolerance. This was a surprise because tests on an earlier batch of the same nominal material showed good radiation tolerance. Therefore it is essential to perform radiation tests on a batch basis for material that is potentially sensitive to radiation damage but is not qualified as radiation hard.

Table 2. Pull strengths for a batch of cover layer used for barrel tapes. The strength of unirradiated samples is compared to that from samples irradiated to 500 kGy(Si).

Sample	Pull strength (N)
Unirradiated	76 ± 5
Irradiated	75 ± 3

7 Conclusion

The large area bus tapes required for the ITk strip detector with long, narrow track and gap lines has been very challenging. Achieving good quality for the nickel/gold-plated pads for wire bonding was difficult. In the case of the barrel tapes, the critical issue was to achieve uniform quality over the length of the tapes. For the end cap tapes the critical issue is the surface roughness after the pads are exposed by laser ablation. The tight requirements on the tape stretch and distortions were particularly challenging. These problems have been addressed and both barrel and end cap tapes are now in production. Copyright CERN for the benefit of the ATLAS Collaboration. CC-BY-4.0 license.

Acknowledgments

The authors acknowledge financial support from the Slovenian Research and Innovation Agency (Project funding No. J1-3032,Spanish R&D grant PID2021-126327OB-C21, funded by

MCIN/AEI/10.13039/501100011033/FEDER, UE, DESY ((Hamburg), Germany), a member of the Helmholtz Association HGF and the STFC (UK). This work was supported in part by the Director, Office of Science, Office of High Energy Physics, of the U.S. Department of Energy under contract No. DE-AC02-05CH11231.

References

[1] ATLAS Collaboration, "Technical Design Report for the ATLAS Inner Tracker Strip Detector." ATLAS-TDR-025, 2017.

[2] L. Gonella, *The ATLAS ITk detector system for the Phase-II LHC upgrade*, *Nucl. Instrum. Meth. A* **1045** (2023) 167597.

[3] A. Boebel et al., *Current status of the end-of-substructure (EoS) card project for the ATLAS strip tracker upgrade using final ASICs*, *JINST* **18** (2023) C03016.

[4] J. Dandoy et al., *Quality control testing of the HCC ASIC for the HL-LHC ATLAS ITk strip detector*, *JINST* **18** (2023) C02026.

[5] ELGOLINE. `https://en.elgoline.si/`.

[6] MEC, "MECBRITE CB5008." `https://www.mec-co.com/en/product/electronic-substrate/`.

[7] ATLAS ITk Strips Collaboration. `https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ITkPublicResults#ITk_Posters_and_Presentations_at`.