PROCEEDINGS OF SCIENCE

Mitigation strategies for sensor fracturing in the ATLAS ITk strips detector

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During Long Shutdown 3 of the LHC, the ATLAS detector will undergo substantial upgrades to prepare for data taking at the future HL-LHC. This includes a replacement of its inner detector with a fully silicon tracker called the ITk, composed of pixel and strip sub-detectors. During the pre-production phase of the ITk strips detector, it was discovered that thermal cycling of the supports loaded with strips modules induces induces physical cracks in some of the sensors. This phenomenon is understood to be the result of a combination of factors, including the thermo-mechanical properties of the module mounting glue, and the relative positions of the module's electric components. These factors combine to create high mechanical stress regions on modules during temperature changes, an effect that must be solved as the detector components must be mechanically robust and able to withstand the planned detector warm-ups and cool-downs during HL-LHC. These proceedings will describe the sensor fracturing mechanism, its signature in electrical test results, and the design and testing of three possible mitigation strategies and their results.

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[*] Speaker

1. Introduction

At the end of Long Shutdown 3 of the Large Hadron Collider running period, the accelerator complex will be upgraded to the High-Luminosity LHC (HL-LHC) in order to increase the amount of data provided to the experiments via an increase in instantaneous luminosity. From this upgrade, the ATLAS [1] detector will have to handle increased pileup, radiation, and rates of data. Consequentially, the ATLAS detector will undergo a substantial upgrade, including a replacement of its inner detector with a fully silicon tracker, called the ITk (Inner Tracker), composed of pixel and strip sub-detectors [2].

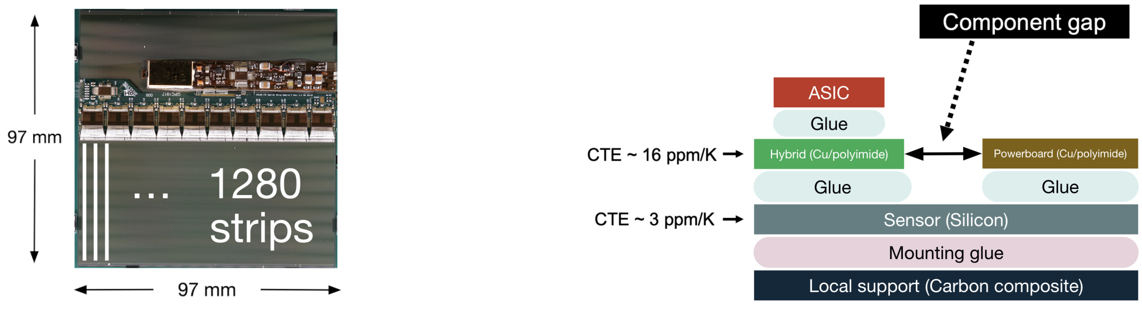
The building block of the ITk strip sub-detector is a module, made of a silicon sensor with electronics glued on top. Modules must be operated at cold temperature in order to minimize leakage current and account for decrease in charge collection efficiency from radiation damage, and therefore have a stringent quality control program including thermal cycling between room temperature and cold. The planned operational temperature of ITk strips modules is -35°C, and sensors may face temperatures as low as -55°C in the possible event of detector failure mechanisms.

During the pre-production phase of the ITk strips detector, it was found that functional modules, when thermal cycled on local support structures, exhibited early breakdowns not seen before mounting. Deeper investigation revealed the formation of physical fractures in the silicon sensor portion of the module. This is understood to be a result of a CTE (Coefficient of Thermal Expansion) mismatch between module layers, and a thin gap between electrical components, leading to high stress on the modules that increases with decrease in temperature. Several strategies have been developed and tested in order to mitigate sensor fracturing.

2. Mechanism

The building block of the ITk strips detector is a module. Modules are built from a silicon sensor, with a "Hybrid" board glued on to host ASICs for data readout, and a powerboard PCB glued on in order to power the readout chips. There are 8 types of modules, 2 for the central region of the tracker (the "barrel") and 6 for the forward regions of the tracker (the "endcaps"), with differing geometries as shown in Figures 2-3 of [3]. While the configurations of components differ among module types, the design concept is the same, with the same stack of material types among all modules. An example ITk strips module is shown from a bird's eye view orientation in Figure 1a. The assembly stack after mounting onto a local support structure, from a side orientation, is shown in Figure 1b.

As shown in Figure 1b, there is a large CTE mismatch between the PCBs and sensor. This means when the module is lowered to cold temperatures, the sensor tends to maintain its shape, while the Hybrid and Powerboard tend to contract. The Hybrid and Powerboard are attached to the sensor using a glue with a high Young's modulus which constrains the sensor's shape to the Hybrid and Powerboard shape. Because the sensor is glued to the local support with a softer glue with a lower Young's modulus, the sensor is not constrained to the support surface, causing the sensor to bend upwards along with the Hybrid and Powerboard. This creates a high stress region with a maximum in the component gap, as shown in Figure 2a, leading to observed cracks, an example for which is shown in Figure 2b.



(a) **(b)**

Figure 1: Left: Image of a Long Strip module. Right: Diagram of a module assembly stack on a local support structure (not to scale).

(a) **(b)**

Figure 2: Left: Simulated module bending. Right: Observed sensor fracture.

3. Signature

Visualizing fractures in modules by eye or with a microscope can be very difficult, even if their location is known. However, damages in the sensor due to fracturing leads to changes in module electrical test results. Namely, sensor fracturing typically induces early breakdown in I-V curves and sporadic noise signatures among strips.

Figure 3a shows an example module I-V curve, in which sensor leakage current is measured as a function of bias voltage, before and after fracturing. It can be seen that before fracturing, the current levels around 100-200 nA, expected for this type of module. After fracturing, the current magnitude increases by a factor of about 10-20, and an early breakdown is seen around -40 volts, far from the planned operational voltage of -350 volts.

Figure 3b shows an example noise measurement of 1280 strips on a Long Strip module, before and after fracturing. Before fracturing, a relatively flat noise distribution around 1000 ENC (Equivalent Noise Charge) is seen. After fracturing, large groups of strips see increases in noise up to around 15-20%, e.g. around strip numbers 950-1100. Additionally, low and high noise values are seen in several regions, e.g. around strip numbers 150-200 and 1150-1200.

4. Mitigation strategies

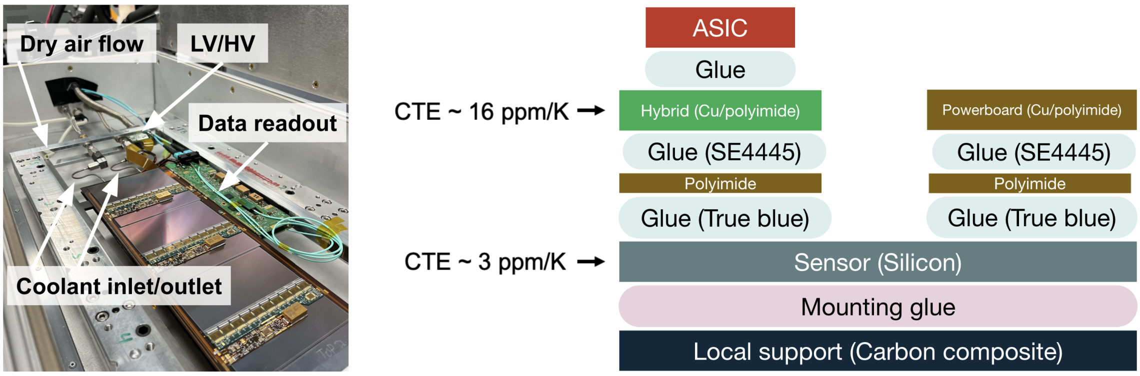
In order to reduce module stress after going cold while mounted on support structures, three mitigation strategies were developed and tested. Throughout the development and testing of these

(a) **(b)**

Figure 3: Example of module electrical test results before and after fracturing, shown in green and red respectively, for a Long Strip module. Left: I-V curve. Right: Noise measurement.

strategies, simulation was utilized to estimate expected changes in module stress [4]. While more precise quantitative results from simulation still require additional data, relative changes between different strategies qualitatively indicate which strategies are more effective than others and motivate testing with physical objects.

When testing strategies, local support structures with mounted modules can be cooled via monophase cooling, with coolant flowing through titanium pipes [5], 2-phase cooling where liquid CO_2 flows through local support structure piping, and in a climate chamber where air cools the environment surrounding the local support structures. An example testing setup for barrel Staves using monophase cooling is shown in Figure 4a. To ensure modules remain robust at their planned operational temperature of -35°C, and as low as -55°C in the event of possible detector failure mechanisms, it is desirable for strategies to be effective at temperatures lower than -55°C.



(a) **(b)**

Figure 4: Left: Mitigation strategy testing setup. Right: Interposer module stackup (not to scale).

The first attempted mitigation strategy was a replacement of the module mounting glue, indicated in pink in Figure 1b, from Dow Corning SE 4445 CV (“SE4445") [6] to Loctite EA 9396 Aero (“Hysol") [7]. As Hysol is a more rigid adhesive than SE4445, it is expected to be more effective at holding modules in place to counteract the sensor bending shown in Figure 2a. The advantage of this strategy is it does not require a change in module design, and can be more easily applied to the existing workflow and to all 8 module types.

The “Wide-gap" strategy is an increase in the component gap between the Hybrid and Powerboard, as shown in Figure 1b, from 1mm to 3mm. This is expected to decrease the “Max Stress" shown in 2a, as it increases the distance over which the sensor bends back down on the powerboard side, spreading the mechanical stress over a wider region. The advantage of this strategy is a large decrease in the expected sensor stress. The disadvantage is that it requires tooling changes for module assembly, and cannot be applied to all module types due to differing geometries and component placement among types.

The “Interposer" strategy is the placement of a 50 micron layer of polyimide (Kapton), and a low stiffness glue layer between the sensor and boards, shown in Figure 4b. Adding this low stiffness glue layer is expected to decouple the deformation of the electronics components from the silicon sensor, while the Kapton layer is there as a separator.

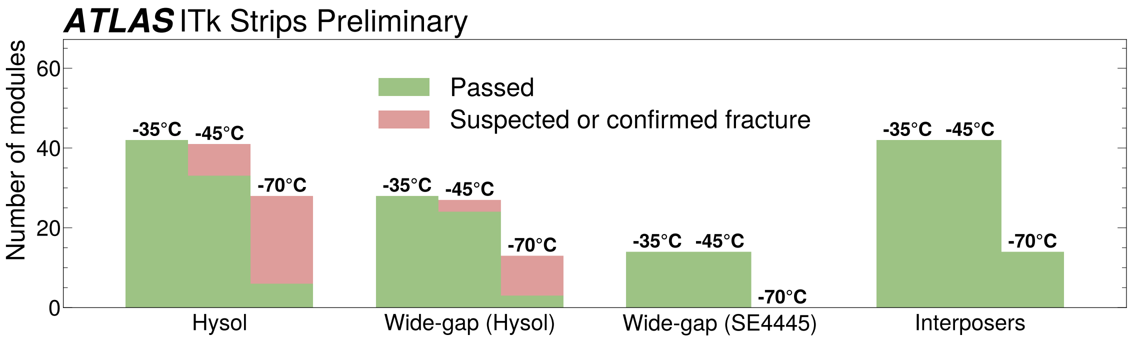


Figure 5: Summary of mitigation strategies and their results.

A summary of the mitigation strategies and their results for barrel modules is shown in Figure 5. Modules mounted with Hysol do not exhibit fracturing at -35°C, indicating an improvement over the nominal module and mounting design which showed fractures after testing at -35°C. They do show fracturing at -45°C, indicating this is not an effective strategy. Wide-gap modules mounted with Hysol also show fracturing at -45°C, indicating it is not an effective strategy. Wide-gap modules mounted with SE4445 do not yet show fracturing, but will be further tested down to -70°C. It should be noted that this would not be an ideal solution due to the required changes in tooling and inability to apply to all module types. So far, no interposer modules have shown fracturing down to -70°C, making it the most effective and desirable solution to sensor fracturing so far.

5. Conclusions

During the pre-production phase of the ITk strips, it was observed that some modules experience fracturing after being mounted onto support structures and cooled to low temperatures. Several mitigation strategies have been developed and tested. So far, the most promising and desirable strategy is the “Interposer" strategy, which will continue to be tested on further objects.

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