Characterization of silicon sensors measuring current versus voltage for the ATLAS Inner Tracker

Emily Duden
Advisor: Prof. Gabriella Sciolla

Brandeis University Department of Physics
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Abstract

In anticipation of the High-Luminosity phase of the LHC, the ATLAS experiment is working on major detector upgrades to prepare for the subsequent increase in radiation and track density. The largest of these upgrades is the replacement of the current tracking detectors with the Inner Tracker, or ITk. In the outer region of the ITk is the Strip Detector, which consists of silicon strip modules. Characterizing the electrical properties of the silicon strip modules at different stages of the assembly procedure is crucial to assessing module performance; this ensures any fault is captured at the earliest possible stage. One of the most important tests is the IV scan, which measures the silicon sensor current (I) as a function of voltage (V). Since the current as a function of voltage provides an indirect measure of the noise, the depletion voltage, and the breakdown voltage, IV scans allow us to determine whether the sensor performance is within specifications. This paper will summarize the IV scanning procedures I have developed and implemented, encompassing three stages of the module's assembly. These procedures include the development of a novel IV scan using the Autonomous Monitor and Control chip, a custom ASIC mounted on each module. This will allow us to diagnose problematic modules after they are mounted on staves and in the ATLAS detector. I will also discuss my work on the configuration and analysis of these test results.

Contents

1 Introduction

The Large Hadron Collider (LHC) is the most advanced facility in the world for investigating matter at its smallest scale. Since it began taking data in 2010, it has made strides in answering questions concerning the origin of mass and investigating the nature of dark matter, the nature of quark-gluon plasma, and new forces and particles. Notably, the 2012 discovery of the Higgs boson at the LHC and subsequent study of its properties and decays shed new light on the origin of mass and fundamental structure of matter. With a collision energy of 13.6 TeV, the LHC operates at the highest energy of any particle collider in the world and thus possesses a unique opportunity to probe the energy frontier [1].

To observe low-probability phenomena, it is necessary to increase the luminosity of the LHC and therefore the volume of data collected. This will be achieved by the High-Luminosity LHC (HL-LHC), an upgrade to the LHC accelerator expected to be fully operational by 2028. The associated increase in instantaneous luminosity will ensure that the LHC will continue to be at the forefront of particle physics for the next decades. Presently, the record LHC luminosity is 2.06×10^{34} cm^{-2} s^{-1}; the HL-LHC will increase this to a peak instantaneous luminosity of 7.5×10^{34} cm^{-2} s^{-1} [1]. With this increased luminosity, the LHC will provide sensitivity to sectors of BSM physics that are currently beyond the reach of analyses and will substantially improve our understanding of the Higgs properties and their relation to electroweak phenomena [2].

ATLAS is the largest of two general-purpose particle detectors at the LHC. Currently, the first part of the ATLAS detector to measure electrically charged particles produced in the LHC's proton-proton collision is the Inner Detector (ID), which measures direction, momentum, and charge. Surrounding the ID are calorimeters that measure particle energy. Muons, which normally pass through the Inner Detector and Calorimeter undetected, are identified and measured by the Muon Spectrometer.

2 The ITk

The Inner Tracker, or ITk, will replace the current ATLAS Inner Detector in 2028. This detector will enable the collection of an order of magnitude more data than what will be collected prior to the HL-LHC. The ITk is an all-silicon detector consisting of a pixel detector at small radius close to the beam line and a large-area strip tracking detector surrounding it. A visualization of the ITk is shown in Fig. 1.

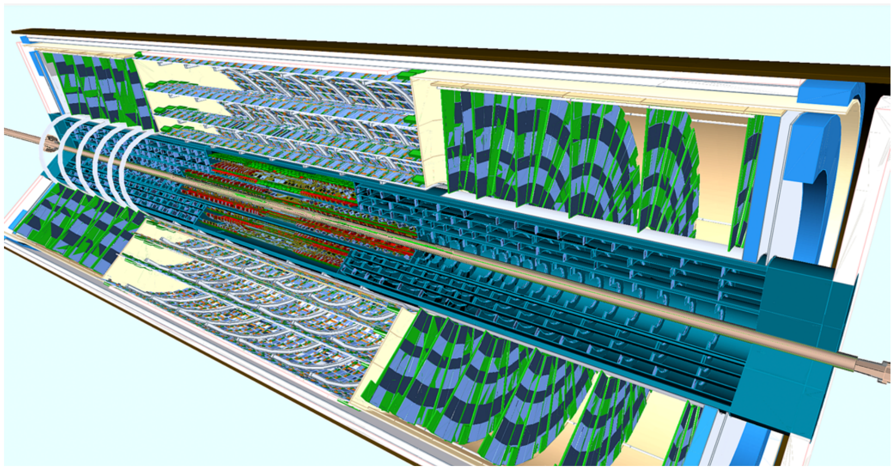

FIG 1: Visualization of the ITk as implemented in the simulation framework. The Pixel detector, shown in teal close to the beamline, is surrounded by the Strip detector [1].

2.1 Motivation

The current ATLAS Inner Detector was designed to operate for 10 years at a constant luminosity of 1×10^{34} cm^{-2} s^{-1} and an average of 23 inelastic proton-proton collisions per beam-crossing (known as the pile-up). By 2016, the ID routinely exceeded its design parameters, taking data at an instantaneous luminosity of 2.06×10^{34} cm^{-2} s^{-1} and a pileup of up to 60 collisions per crossing [3]. Unfortunately, the high luminosity and associated data rate and accumulated radiation damage will render the Inner Detector inoperable in the HL-LHC environment. The ITk was designed for the challenges associated with high luminosity, which are detailed below.

1. Radiation damage: the HL-LHC will result in an accumulated integrated luminosity of 3000 fb^{-1}. The current ATLAS tracker, particularly the Pixel detector, is designed to withstand up to 400 fb^{-1}. Above this luminosity, efficient pattern recognition will not be possible and the leakage current from the detector will overwhelm the cooling system and exceed power supply limits.
2. Bandwidth saturation: the front-end electronics of the current ID do not suppress data collection in order to minimize the data volume along optical fibers which transport information. The pile-up of the HL-LHC will reach up to 200 proton-proton interactions per beam crossing, four times what the ID was designed to accommodate. As a result, ID operation in the HL-LHC would result in bandwidth saturation and loss of data.
3. Limitations from detector occupancy: the granularity of the current ID is not sufficient to resolve the expected average pile-up of 200 proton-proton interactions per bunch crossing. The increase in hits would make efficient pattern recognition impossible and prevent accurate track reconstruction, increasing the frequency of fake tracks and resulting in difficulties resolving nearby tracks.

The ITk will be able to withstand the challenging environment presented by the HL-LHC while offering improvements in data quality [1]. Radiation hardness in the ITk is improved by new sensor doping technology and the development of radiation hard ASICs. Progress in ASIC development has also resulted in the ITk's readout electronics having a larger bandwidth. Finally, the ITk will boast granularity improvements. This will be facilitated by a greater number of pixel layers and more and smaller strips in the strip layers.

2.2 Layout

The ITk will consist of an inner Pixel detector surrounded by an outer Strip detector. The ITk layout is shown in Fig. 2. The Pixel detector is shown in red; it will have five cylindrical barrel layers in the central region and several pixel rings on the forward region. The Strip detector is shown in blue; it will have four barrel layers, each of length 2.8 m, and seven disks on either side. The Pixel detector has high granularity and is thus ideal for the high occupancy region close to the beamline, while the Strip detector is more cost effective.

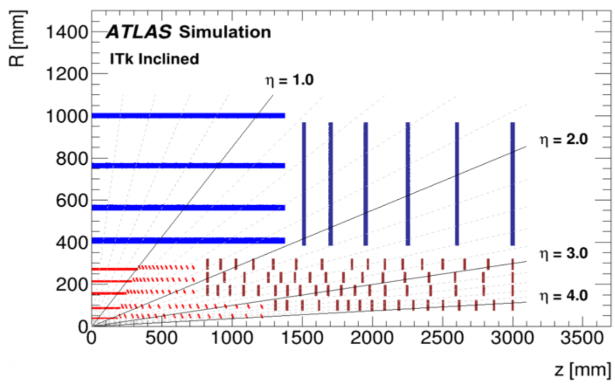

FIG 2: Cross section of one quadrant of the ITk showing the location of active detector elements. The Pixel detector is shown in red and the Strip detector is shown in blue. The horizontal direction corresponds to the axis along the beamline. Horizontal and vertical lines represent barrel and end-cap layers, respectively [1].

This Strip barrel detector consists of 392 "staves", rectangular units with approximate area 140 × 10 cm^2. Mechanical support for silicon sensors and housing for the electrical, optical, and cooling services is provided by the staves. Each stave consists of 28 silicon-strip modules mounted on a carbon composite core. A module is a 9.8 × 9.8 cm^2 single-sided silicon strip sensor outfitted with readout ICs and control circuitry. The inner two layers of the Strip detector use short-strip modules while the outer layers use long-strip modules; short-strip modules, with strip length 24.1 mm, are necessary in the high-occupancy regions at small radii, while long-strip modules, with 48.2 mm strip length, are sufficient for the two outer layers [1].

3 ITk Strip Barrel Modules

Modules are the basic unit of the Strip detector. A module consists of one silicon strip sensor, one to two PCBs that host the readout ASICS called hybrids, and one power board, which hosts a low-voltage power converter and high-voltage switching circuit. Mounted on each barrel-layer hybrid are 11 read-out ASICS: ten ATLAS Binary Chips (ABCStars) and one Hybrid Controller Chip (HCCStar). Signal from the strips is inputted into an ABCStar, amplified, shaped, and discriminated. This signal is then outputted to the HCCStar, which ships information out of the module. A schematic of a short-strip barrel module is shown in Fig. 3.

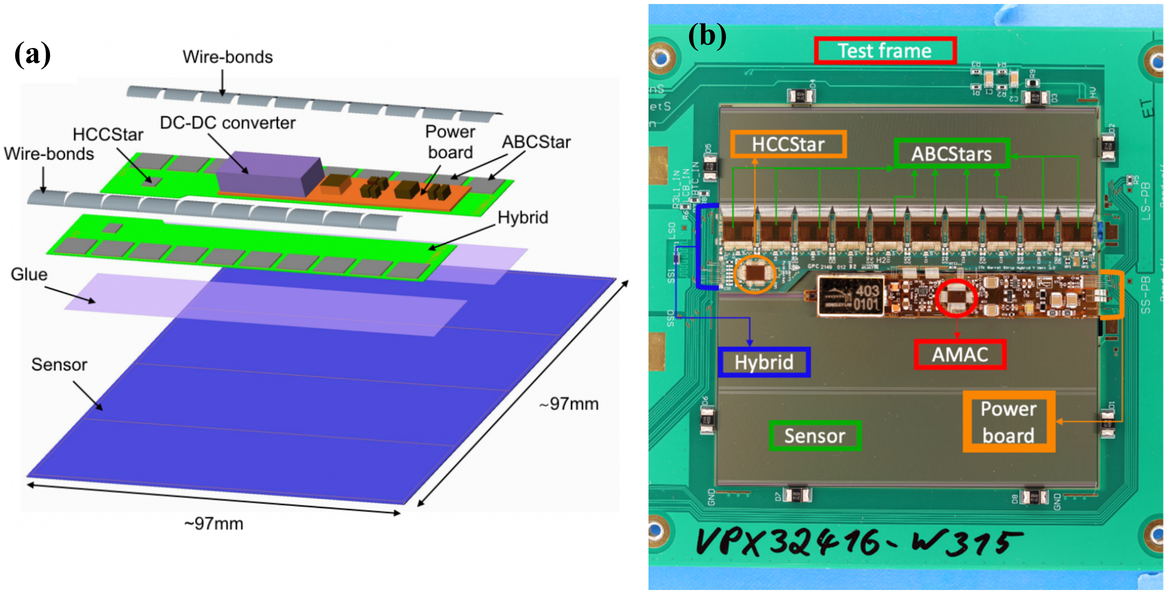

FIG 3: (a) Exploded view of a short-strip barrel module. Long-strip modules have only one hybrid [1]. (b) Short-strip barrel module on test frame before second hybrid is glued.

For high voltage (HV) to be supplied to a module, an HV-tab must be added to the sensor. This tab is bonded to the backplane of the sensor without wire and wire bonded to a test frame so that high voltage may be supplied. A front view of an HV-tab during testing is shown in Fig. 4. When a module is loaded, the tab is bonded to the bus tape which provides electrical connections to modules on the stave.

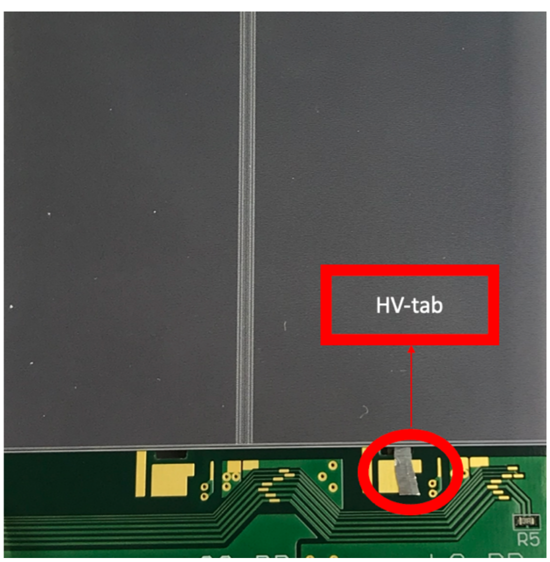

FIG 4: HV-tabbed sensor during testing.

4 The AMAC Chip

The power board hosts the Autonomous Monitor And Control (AMAC) chip (see Fig. 3b), a custom ASIC responsible for the module's infrastructure. The AMAC performs environmental measurements and has interlock functionality, which includes switching off the high voltage supplied to a module. It can measure voltages, temperatures, and sensor bias current on strip modules at a rate of approximately one sample per millisecond. AMAC sensor bias current measurements are shown in Sec. 5.3.

The "heart" of the AMAC is the Analog Monitor (AM), a 16 channel Wilkinson Analog to Digital Converter. The readout of each channel allows measurements such as temperature and current. The most recent version of the AMAC, AMACStar, has 61 internal configuration registers that may be set in order to control the chip. 13 of these are status registers that can be read to provide measured values as well as other status information.

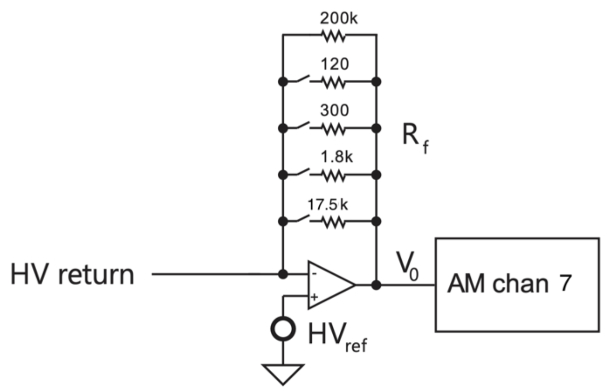

FIG 5: AMACStar HV return current measuring circuit. The selectable range of feedback resistors allow for a range of current measurements [4].

The AMAC's HV return current measuring circuit is shown in Fig. 5. The HV return is fed to an op amp with a selectable range of feedback resistors that adjust the overall gain of the circuit. The 200 $k\Omega$ resistor is always in the feedback loop. Additional switches may be closed via register 50 to include any combination of the other four resistors.

Sw. setting	Feedback R (Ω)	Current Range
4'b1100	120//300	up to 8 mA
4'b1000	120	250 μA – 5.7 mA
4'b0100	300	100 μA – 2.4 mA
4'b0010	1.8k	40 μA – 470 μA
4'b0001	17.5k	150 nA – 50 μA
4'b0000	200k	0 – 4.5 μA

TABLE 1: Current range associated with each combination of feedback resistors in the HV return current measuring circuit and the associated switch (Sw.) setting. Each switch setting indicates the binary number the "HV Gain" bits in the relevant register is set to (the prefix "4'b" indicates a 4-bit binary number).

Since the AM is an ADC, reading an AMAC channel yields ADC counts (ADC_i), which can be translated to a voltage using a conversion factor (m) obtained by doing calibration ramps. With the zero/offset value of the AM channel (ADC_{off}) and the total feedback resistance (R_f), the HV return current (the current in the sensor) can be calculated:

$$I = \frac{m(ADC_i - ADC_{off})}{R_f}. \quad (1)$$

Each combination of feedback resistors is associated with a current "range" that can be set via register 50. Table 1 shows the current range associated with each feedback resistance.

5 IV Scans

5.1 Motivation

According to the ITk Quality Assurance (QA) and Quality Control (QC) measures, each module must be rigorously tested at each stage in development. This ensures the module's successful performance throughout its lifetime in the ITk as well as efficiency and effectiveness during production. One necessary test is the IV scan, which measures the bias current through the sensor as a function of applied voltage. An example of an IV scan performed on a healthy sensor is shown in Fig. 6. The primary purpose of an IV scan is to identify whether the sensor experiences electrical breakdown before the QA/QC determined voltage and if so, at which voltage this occurs. Sensor specifications dictate that a sensor should have a breakdown voltage above 700V. Due to sensitive ASICS on the power board, a voltage above 550V should never be applied to a module. A stave-ready module should not exhibit a breakdown voltage when tested up to this voltage. Early-breakdown sensors and modules may not proceed to the next stage of development.

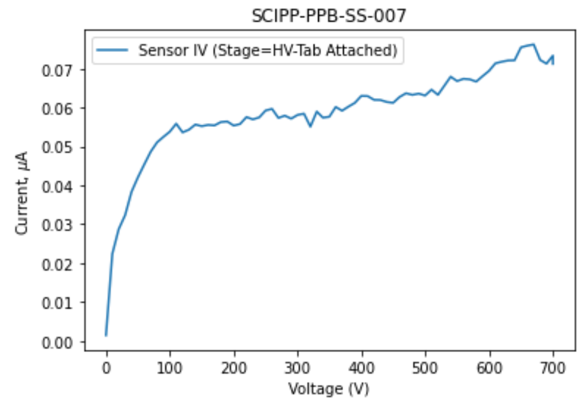

FIG 6: Example IV scan done on a healthy sensor. Here, the current exhibits no sharp increases and remains solidly within the 0-0.2 μA range, indicating that no early breakdown has occurred.

Early breakdown can be caused by a variety of issues in the module and testing setup. Light may excite electrons on the sensor to the conduction band, causing additional current. Faulty wirebonds can direct additional current through the sensor or compromise the sensor current. A rapid increase in bias voltage can cause oscillations in current that lead to sensor break down. When a sensor does not pass its IV test, problems with the sensor or testing setup can sometimes be identified and remedied; other times, the sensor itself is compromised and discarded.

After performing an IV test on an ITk component, the data is uploaded to the ITk Production Database, a platform for monitoring component location and stage as well as storing test results. Additionally, the analysis on the IV curve is performed, primarily to determine whether the sensor went into early breakdown, and the results of this analysis also must be uploaded to the database. Analysis is sometimes done as part of the testing process and sometimes done during database upload.

5.2 Bare Sensor and HV-Tabbed Sensor IV Scans

Before the powerboard is mounted on the sensor, an IV scan of the bare sensor is taken. One of the most common ways to take an IV scan is using the ITk Strips Data AcQuisition software, ITSDAQ. ITSDAQ is ROOT-based software and firmware for data acquisition in the ATLAS Strips Upgrade project. When taking a sensor IV scan, the ITSDAQ software communicates with the power supply to ramp up, ramp down, and collect voltage and current measurements.

Before testing, the sensor is placed on a test frame which provides mechanical rigidity and support during the testing process and electrical connections to supply power and for readout purposes (see Fig. 3). The sensor remains on the test frame until the module is loaded onto the stave (except during the hybrid and powerboard mounting process, when an assembly jig is used). The power supply is connected directly to the test frame. When mounted on the test frame, the sensor is in series with a 1 $M\Omega$ resistor, which limits inrush currents.

IV scans must be performed at specific temperature and humidity ranges which are detailed in the Appendix. At BNL, all IV scans are performed within a custom reception box built by Harvard and BNL (Fig. 7) which hosts sensors to measure environmental conditions. This reception box also features four sensor/module "chucks" that are designed to hold the test frame. Each chuck has power supply connections that may be plugged into the test frame. When testing, ITSDAQ can read up to four modules in parallel.

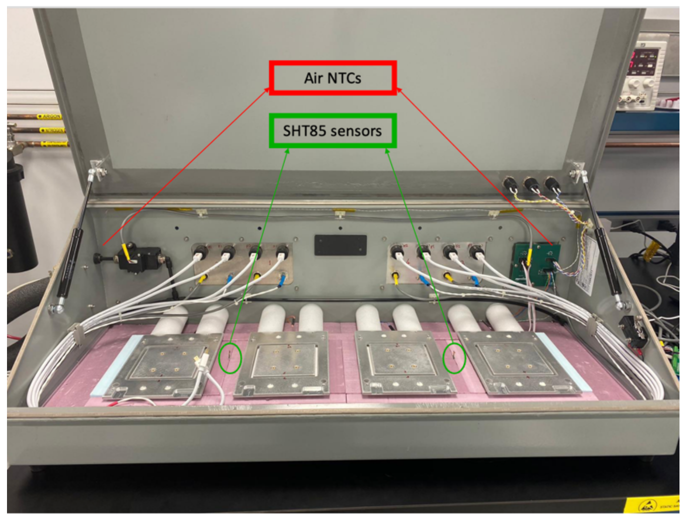

FIG 7: Reception box at BNL for testing modules and sensors. SHT85 sensor and air NTC thermistor locations are indicated.

IV measurements are taken up to a bias voltage of 700V, applied in 10V/10s increments. Just before each voltage increase, the current is sampled to ensure it does not exceed 20 μA. If this current is reached, the test is aborted. Upon reaching 700V, a 30 second stability test of three current measurements at 700V is performed. Finally, the voltage is ramped down at a rate of 10V/s and an output file is produced.

As part of my work in the summer of 2021, I helped develop a graphical user interface (GUI) in ITSDAQ to automatically run the sensor IV test with appropriate default parameters. These parameters include starting and stopping voltage, voltage step, current limit, and delay between measurements. Several parameters that must be written to the output file, such as sensor or module serial number and the sensor's stage in production, must also be manually entered. These include temperature and humidity measurements. Additionally, the GUI has optional fields for comments and run number—if no run number is entered, ITSDAQ automatically generates one.

There are two dedicated tests in the ITk Production Database for sensor IVs: "Sensor IV" and "Module IV taken with power supply". This is because the database considers sensors after HV-tabbing to be modules, though the power board and hybrid(s) are not yet mounted. The procedure for these tests, in which the power supply applies a voltage to the sensor via the bias ring and measures the resulting current, is identical. However, the database test structure (and thus the output file format for these two tests) are different. I created the database object for the

HV-tabbed sensor IV. For both tests, I wrote code in ITSDAQ to ensure the output file format contains all required fields and is database compliant. The agreed upon output format of sensor IV scans is a DAT file consisting of a header which includes testing parameters, identifying information, and institution specific documentation, followed by voltage and current columns.

I performed many IV tests on both bare and HV-tabbed sensors at BNL during the summer of 2022. Examples of such test results are shown in Fig. 8. These tests were performed as part of Pre-production B (PPB), a stage in ITk production using final components that will prove that the collaboration can produce production-quality strip modules in large amounts. The maximum current of a healthy sensor should not exceed ~0.2 μA.

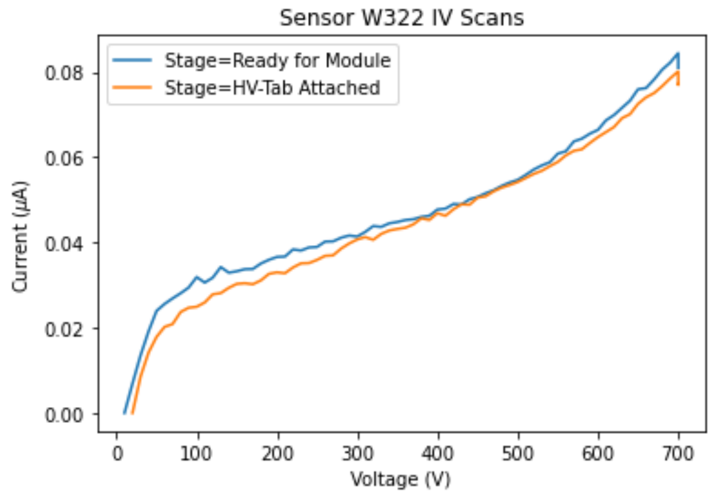

FIG 8: IV scans on sensor W322 at stages “Ready for Module” and “HV-Tab Attached” taken as part of PPB at BNL.

I also worked on software for uploading the test results to the ITk Production Database. To upload data to the database, a JSON object must be produced from the DAT file, the data pulled from the JSON object for analysis, and analysis parameters added to it before it can be directly uploaded. Bare sensor IV upload and analysis via Python scripts was already implemented when my work on sensor IVs began in May of 2021. My work consisted of adapting these scripts to upload tests with the HV-tabbed sensor output format.

5.3 Module IV Scans with AMAC

Once the hybrid(s) and power board have been mounted on a sensor, it is possible to measure the current on the sensor with the AMAC chip instead of the external power supply. This capability is very advantageous because after the modules are loaded on the stave and mounted inside the ATLAS detector, electrical connections permitting the measurement of an individual sensor become impossible. With the AMAC, we might measure the current on an individual module throughout the module’s lifetime, allowing us to identify and promptly disable problematic modules at any point in time during the 10-year operation of the ITk.

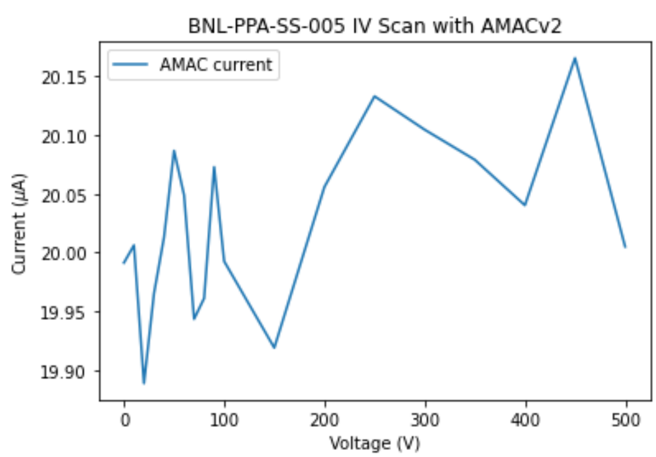

FIG 9: IV scan taken with the old version of the AMAC on a BNL PPA module. Clearly, this AMAC is not able to provide a real current measurement.

The ability of the AMAC to take a meaningful IV scan was unclear prior to my work at BNL this summer. Previous studies with an older version of the AMAC indicated that the AMAC was unable to resolve low currents and yielded measurements that were not compatible with the real current known to be in the sensors—these measurements appeared to indicate only noise. When I first started this work, I performed studies using the old AMAC modules and I replicated these results (see Fig 9). While confidence was low that a meaningful IV curve could be produced using the AMAC, it was generally thought that the AMAC could resolve higher currents and indicate at least whether a sensor has gone into breakdown. To investigate this, I performed IV scans on several PPB modules using the latest version of the chip, the AMACStar.

When an IV is taken through the AMAC, ITSDAQ software similarly communicates with the power supply to ramp up, ramp down, and collect measurements. It also communicates with the Nexys board, a data acquisition board that hosts the ITSDAQ firmware. This firmware translates commands for the AMAC issued by software, such as setting registers and taking measurements. The procedure for taking IV scans with the AMAC is detailed in the Appendix.

The AMAC current measurement function used most commonly in ITSDAQ performs auto-ranging, i.e., it automatically chooses the feedback resistor most appropriate for the given current according to Table 1. This feedback resistance, along with the information outputted by the functions above, is sufficient to calculate the current from AMAC counts using Eq. 1. This function also allows averaging over multiple individual measurements to obtain a more accurate current. All results reported below were obtained by averaging over 1000 individual measurements, which takes no more than five seconds.

At BNL, I performed IV scans on four different short-strip PPB modules, all built with AMACStar chips. Three such modules were built at the Santa Cruz Institute for Particle Physics (SCIPP) and one was built at BNL. The BNL module, W315, was built using a sensor that was known to go into breakdown specifically so that the AMAC's ability to catch a breakdown could be tested.

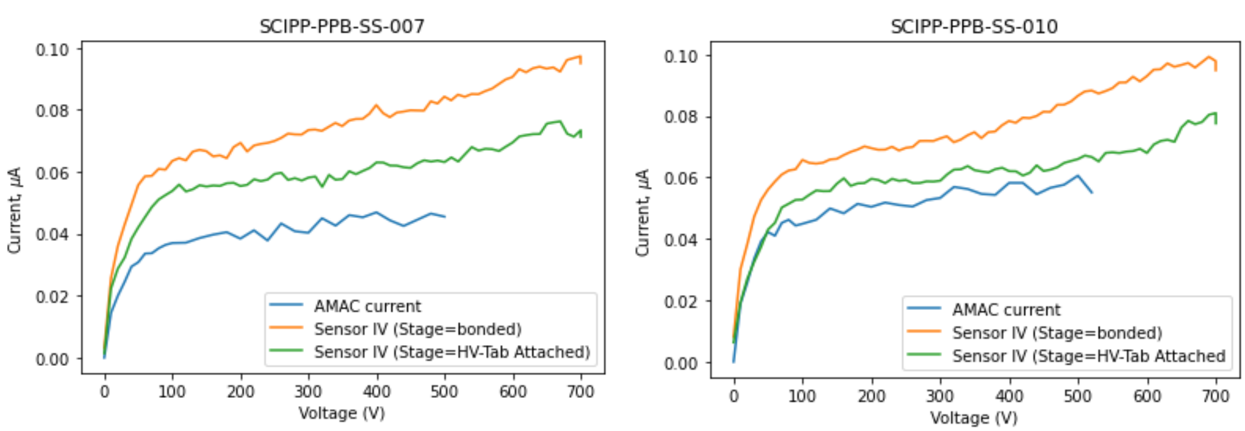

FIG 10: IV Scans at different stages of production for two different SCIPP PPB modules. SCIPP-PPB-SS-007 is shown on the left and SCIPP-PPB-SS-010 on the right. The sensor tests were performed at SCIPP while the AMAC test was performed by me at BNL. These results demonstrate AMACStar's remarkable ability to take real measurements even at low current.

Fig. 10 shows IV scans on two SCIPP modules plotted alongside the sensor IV results at various stages. These results are incredible; the AMACStar appears to not only measure a real current, but also capture the electrical behavior of the sensor in previous stages.

Most importantly, the AMAC must indicate a sensor breakdown. Fig. 11 shows the sensor and module IV scans for the BNL module built from a sensor that prematurely breaks down. While the module breaks down ~100V later than it did on the sensor, this breakdown is still evident, demonstrating for the first time the AMAC's capability of clearly showing a breakdown.

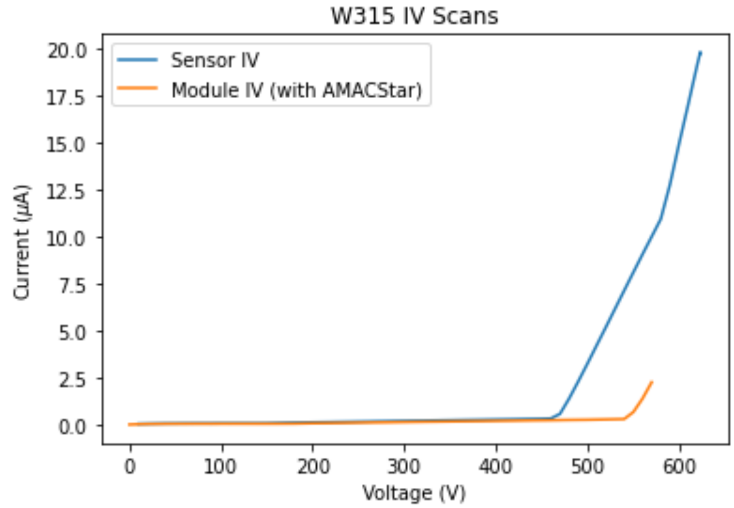

FIG 11: IV Scans taken on sensor W315 before and after being made into a module.

The last SCIPP module's (SCIPP-PPB-SS-011's) IV results are shown in Fig. 12 alongside the previous three module's results. Surprisingly, this module also appeared to go into breakdown. Measurements on this module were halted to prevent further damage and allow us to attempt recovery of the module. The SCIPP-011 results provide evidence that we can identify an unexpected breakdown using the AMAC.

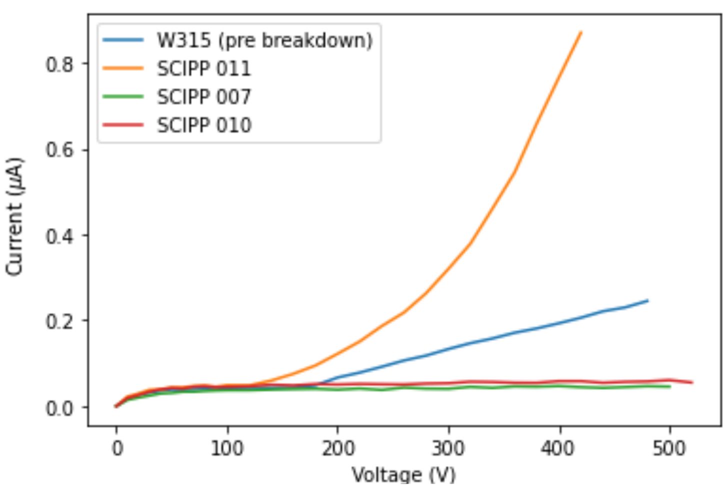

FIG 12: IV scans on four PPB modules taken with AMACStar. W315 was expected to go into breakdown. Note that SCIPP 011 appears to unexpectedly go into breakdown.

Previously, it was agreed that an IV scan using the AMAC must be performed as part of module testing; however, doubt that the AMAC could yield a useful IV curve slowed the implementation of this test. The results of my studies of the AMACStar brought confidence in the AMAC's capabilities. Consequently, I have moved forward with implementing these tests in ITSDAQ. A function to take an automatic IV scan using AMACv2 already existed in ITSDAQ. I adapted this function to work for both AMACv2 and AMACStar. I also created an option in the GUI to take an IV scan with the AMAC; on the front end, this option is almost identical to the sensor IV options, allowing users to set limits, identifying information, environmental measurements, and comments.

While the output format of IV scans taken with the AMAC is still in flux, the ATLAS ITk community has agreed that the upload and analysis process should be streamlined by discarding the production of a DAT file and instead creating a JSON file directly. This means that analysis of IV curves must be done in ITSDAQ and the original external python-based analysis scripts cannot be used. It was also agreed that several fields of data taken by the AMAC should be added to the output. These include the AMAC fuse ID, a unique identifier that can be read from the AMAC, and the temperature of several components on the module. I have already developed a macro that produces the desired JSON output file, though the analysis, which mainly consists of the breakdown voltage calculation, still needs to be added to this output file. I have begun implementing the breakdown voltage calculation in ITSDAQ and will continue this work throughout the semester.

My work concerning taking IVs with ITSDAQ has not yet been merged to the ITSDAQ master branch but can be accessed in the Emily_AMAC_IV branch [5].

6 Conclusion

Over the past year, the ITk collaboration has successfully implemented IV scanning in ITSDAQ for bare and HV-tabbed sensors as well as modules. In addition to performing many IV scans on pre-production B sensors, I made significant contributions to the development of these tests, especially in creating a user-friendly GUI in ITSDAQ. I also adapted existing bare sensor python scripts to upload and analyze HV-tabbed sensor test results to the ITk Production Database.

My main contribution to this project was the demonstration that IV scans can be obtained through the AMACStar chip which, unexpectedly, provides excellent ability to measure a meaningful current in the nanoamp range. This led me to create the functionality in ITSDAQ to automatically take IV scans through the AMACStar and add it to the IV scanning GUI. For both sensor and module IV tests, I have reworked the output file format, ensuring they are database compliant. Work on analyzing IV scans taken with the AMAC is ongoing.

My work has demonstrated that IV measurements can become part of the in-situ ATLAS testing. This will be a major advantage when the detector starts suffering radiation damage because such tests will allow us to identify and exclude damaged modules. Through this work, I have completed my ATLAS Qualification Task, a substantial contribution to ATLAS that qualifies me to be on the ATLAS author list.

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7 Appendix

7.1 IV Scan Environment

IV scans must be performed at a temperature of 21±2 ℃ and humidity of <10%. At BNL, all IV scans are performed within a custom reception box built by Harvard and BNL (Fig. 7). The box is set to an environmental temperature of 20 °C and flushed with ~1.5 standard cubic feet per minute of dry air to ensure 0% humidity. Temperature is monitored with two NTC thermistors in air and humidity is monitored with two SHT85 sensors in air. These sensors are read out by a Raspberry Pi. The web-application Grafana is used for real time visualization of the temperature and humidity data. The reception box also features four sensor/module "chucks" that are designed to hold the test frame. Each chuck has power supply connections that may be plugged into the test frame. The sensors or modules are carefully loaded into the reception box and a 6-position molex connector is attached. This connector can supply both high and low voltage, though only high voltage is necessary for sensor IV scans.

7.2 IV Scan with AMAC Procedure

IV scans taken with the AMAC are also performed in the reception box at 20°C and 0% humidity. For these tests, the low voltage (LV) supplied by the 6-position molex connector is necessary as it provides the 11V necessary for the power board to function. A DisplayPort connection between the AMAC and the Nexys board is also necessary for AMAC IV tests.

Before taking a current measurement with the AMAC, several initialization and calibration functions must first be run in ITSDAQ. These functions and their purpose are:

1. Initialize: initializes vectors to store information.
2. Configure: sets communication with the AMAC and sets registers according to a configuration file.
3. Internal calibrations: finds "zero value" in counts of every AMAC channel.
4. Calibration scan: performs ramp gain calibration, giving a slope in mV/count.

After running these functions, the AMAC is ready to take a current measurement.