

Silicon strip detector system assembly for the ATLAS Inner Tracker upgrade at the LHC

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Abstract

During the past 18 months, I worked on the assembly of the strip detector system at Brookhaven National Laboratory for the Inner Tracker (ITk) detector for the planned upgrade of the ATLAS detector for the High Luminosity LHC. The ITk consists of two concentric silicon sub-detectors, the pixel and the strips detectors. The strip detector consists of 4 layers. Each layer consists of electrical modules glued on the local support structures, or *staves*. This report will discuss the work I did to assemble the first stave using the new-generation chips, ABC* and HCC*, and to perform the required metrology. I will also discuss the modifications to the engineering drawings for the staves to adhere to expected manufacturing standards.

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Preamble

The work shown in this report was done at Brookhaven National Laboratory, Upton, New York by a group comprising of BNL staff and Brandeis University personnel with the support of our colleagues from Harvard University, University of Iowa, Yale University, Oxford University, University of Liverpool, Rutherford Appleton Laboratory, and many others.

While the progress wouldn't have been possible without the help from the many people involved, I am the primary person responsible for operating and modifying the stave assembly software, within the purview of which I mounted 28 long strip modules on a stave core. Furthermore, all the measurements shown in this report, including stave metrology, bus-tape metrology, and module metrology, were made by me during the last 18 months, either for drawing validation purposes or as a part of the Quality Assurance / Quality Control process.

Based on the results I obtained using the multiple rounds of measurements, the ITk Stave Core and Stave Assembly team decided to modify the engineering drawings for the stave core and bus tape. The work on the stave assembly algorithm modifications are still underway, and the final decision will be made according a few more measurements that I will make on the current stave core over the next months.

1 Introduction

The Large Hadron Collider (LHC) is the most advanced facility in the world for the investigation of the structure of matter at smallest scales and has already made substantial progress in addressing these questions. Since its start-up in 2010, the accelerator has delivered collisions at an increasing rate and at the highest energy ever reached in colliders: 13 TeV in the proton-proton centre-of-mass system. In 2012, the successful operation of the LHC resulted in the discovery of a new particle, which was confirmed to be a Higgs boson.

As the world’s highest energy facility with an ambitious programme to greatly extend the statistical sensitivity to new physics, the LHC will be at the forefront of high energy physics for the next 20 years. This potential is the reason that the high luminosity (HL-LHC) upgrade [1] was approved. The scientific programme of the LHC includes an ambitious series of upgrades that will ultimately result in an accumulated integrated luminosity for proton-proton collisions of 3000 fb^{-1} . This represents an order of magnitude more data than what would be collected prior to the HL-LHC run. The improvements necessary to achieve this performance will be mostly realized during two long shutdowns. Long Shutdown 3 (LS3) starting at the end of 2024 will include major performance upgrades of the accelerator for the high-luminosity phase (HL-LHC) which requires replacement of several major detector components (Phase-II). The projected timeline for the upgrade of the LHC is illustrated in Fig. 1.

With a nominal (ultimate) luminosity of $\mathcal{L} = 5 \times 10^{34} \text{ (} 7.5 \times 10^{34} \text{) cm}^{-2} \text{ s}^{-1}$ and an average $\langle \mu \rangle = 140 \text{ (} 200 \text{)}$ inelastic proton-proton collisions per beam-crossing, also called the luminosity, the HL-LHC will present an extremely challenging environment to the ATLAS experiment, well beyond that for which it was designed. The anticipated increased luminosity, along with the associated data rate and accumulated radiation damage, will render the current ATLAS inner tracker inoperable. The ATLAS collaboration decided that it will replace the tracking system with a new all-silicon tracker to maintain tracking performance in this high-occupancy environment and to cope with the increase of approximately a factor of ten in the integrated radiation dose.

Fig. 2 shows a simulated schematic of the ITk tracking system, with five barrel layers of the Pixel Detector and four barrel layers of the Strip Detector in the central region. The Strip Detector consists of two short-strip layers of paired stereo modules followed by two long-strip layers of paired stereo modules. The forward regions will be covered by six strip disks and a number of pixel rings leading to one or more hits depending on the ring layer and η (pseudo-rapidity) position. The layout of the Strip Detector is discussed in detail in Section 2.

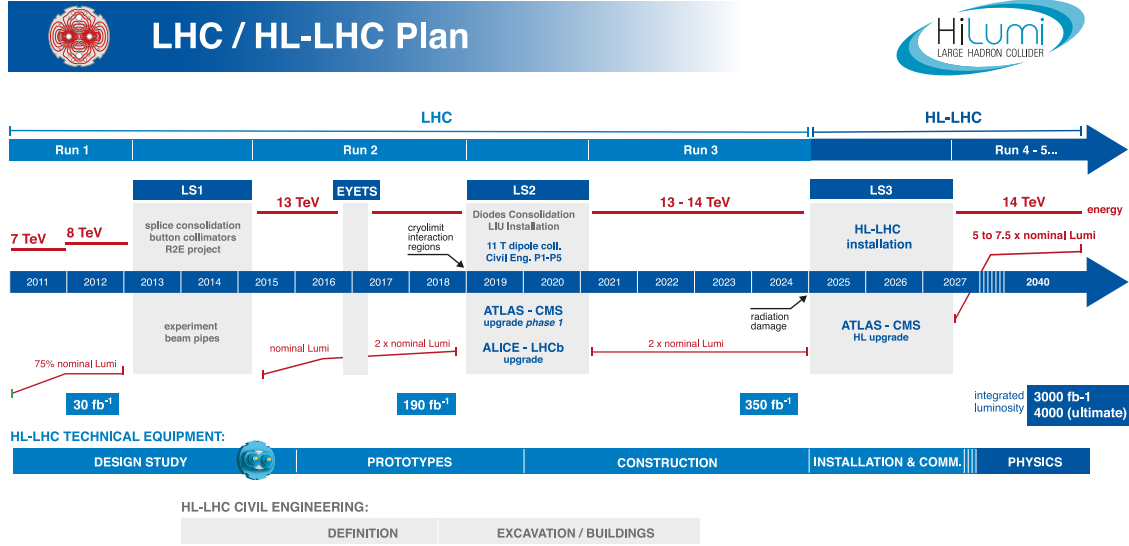


Figure 1: Timeline of the LHC baseline programme and its upgrade phases, showing the energy of the collisions (upper line) and instantaneous luminosity (lower lines). After the third long shutdown (LS3) in 2024-2026, the machine will be in the HL-LHC configuration [1].

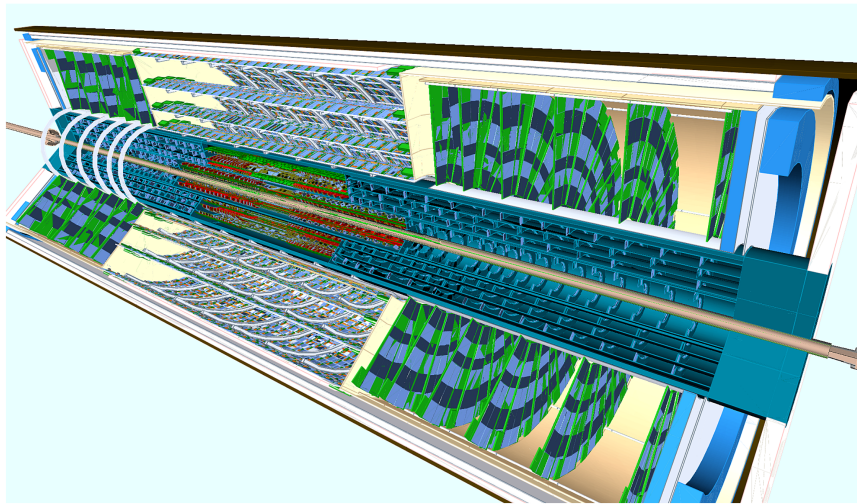


Figure 2: A visualisation of the ITk as implemented in the simulation framework [2].

2 The Inner Tracker Strip Detector

The HL-LHC will run at much more severe operating conditions than the LHC and in the presence of 200 superimposed minimum bias events. This poses a challenge to the ATLAS experiment, that is to deliver equal or even better tracking performance, for physics objects of interest, to that provided by the current tracking system during the present data taking at the LHC. The ITk has been designed to achieve this requirement, and this section will summarize the optimized layout of this detector.

2.1 Motivation

The current ATLAS Inner Tracking Detector was designed for 10 years of operation at a constant instantaneous luminosity of $\mathcal{L} = 1.0 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, 14 TeV centre-of-mass energy, and an average pileup of 23 proton-proton interactions per crossing. In 2016, both the instantaneous luminosity as well as the average pileup was increased. With upgrades to the Pixel detector and the insertion of a new innermost B-layer, the tracking detector has proved to be more than suitable to work as designed in these conditions. The specifications for the radiation tolerances of these detectors are sufficient to guarantee high efficiency for the integrate luminosity expected to be collected by 2024, but no longer than that. Above the design fluences, the detector loses hit efficiency below the required limits and the leakage current will exceed the capacity of the power supply as well as the cooling system.

The front-end electronics of the current detectors do not employ any suppression to the data volume. The detectors can accommodate events with not more than 50 proton-proton interactions per crossing which comes at twice the current design instantaneous luminosity. This is clearly not enough for the run parameters expected for the High Luminosity upgrade. Apart from the rate, the current readout system also cannot handle increased data occupancy which comes as a consequence of additional hits without an increase in granularity.

2.2 Layout

The ITk is an all-silicon detector consisting of a pixel subsystem with a pseudorapidity coverage of $|\eta| < 4$ and a strip subsystem covering the interval $|\eta| < 2.7$. The pixel subsystem consists of five flat barrel layers and five layers of inclined or vertical rings providing coverage in the forward region [3]. The strip subsystem comprises four strip

module layers in the barrel region and six disks in the end-caps. Figure 3 shows the ITk layout in the $R - z$ coordinates, where the blue lines represent the strip detectors in the barrel and endcap regions.

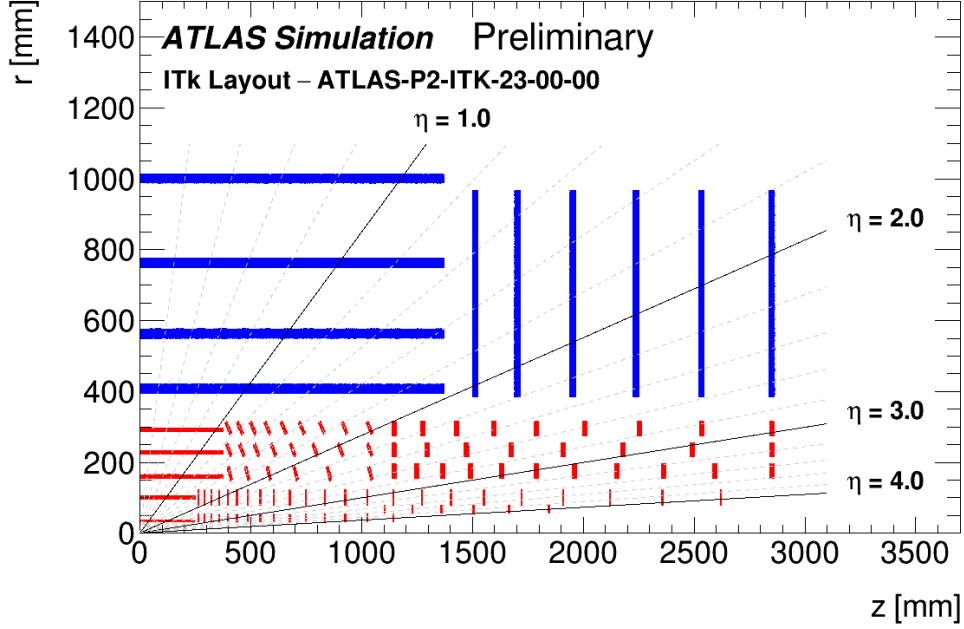


Figure 3: The schematic depiction of the ITk Layout, including the updated layout for the Pixel detector. Only one quadrant and only active detector elements are shown. The active elements of the strip detector are shown in blue, and those of the pixel detector are shown in red. The horizontal axis is along the beam line with zero being the interaction point. The vertical axis is the radius measured from the interaction region [3].

This report will mainly talk about the strip detectors in the barrel region. As outlined in Section 1, there are four barrel layers, the inner two consisting of staves mounted with short strip modules and the outer two with long strip modules.

The detector units, also called *staves* due to them combining to form barrels, are asymmetric structures with the data readout connectors at the two ends (away from the centre of the detector which is at $z=0$). This asymmetry gives a sense of handedness to the system and hence classifies a unit as being a staffe on side 'C' of the detector or being on side 'A' of the detector. A representative side view of the system is shown in Figure 4.

The EoS PCBs are end of substructure readout components with one on each side of the staffe, attached in a master-slave configuration.

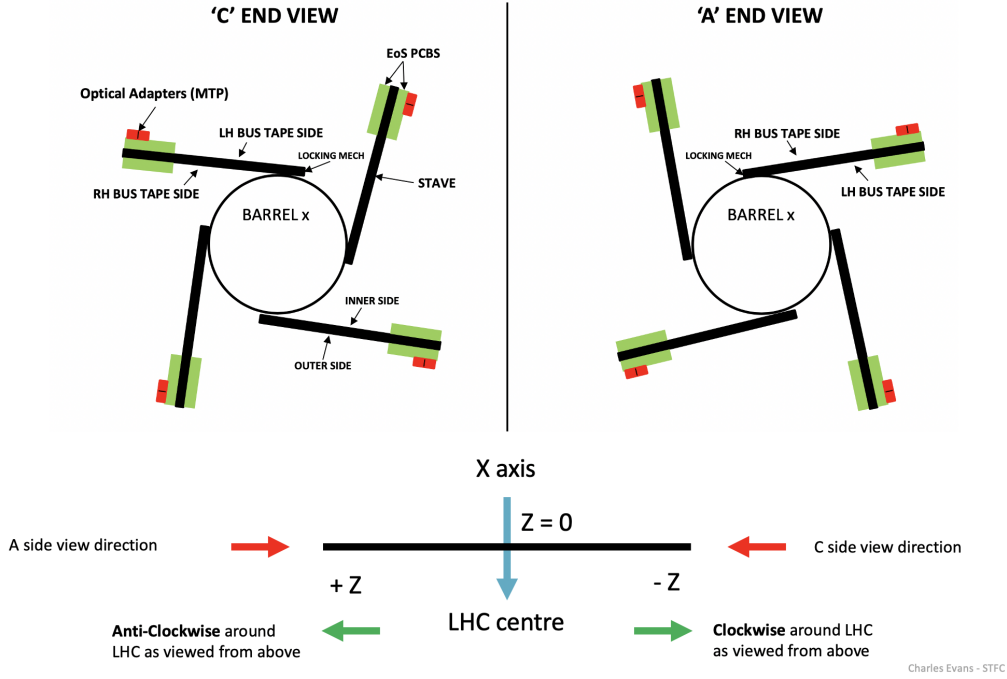


Figure 4: In the Right-handed coordinate system, all barrel staves are rotated around the Z-axis by a negative angle. Positive angle is defined as a rotation from the positive X-axis towards the positive Y-axis. The top diagrams are projections as seen from $z=0$, where 'C' end view has staves going anti-clockwise and 'A' end view has staves going clockwise. The sense of rotation is reversed when seen from above, as shown in the diagram below. [Source - Charles Evans (STFC), Tony Weidberg (Oxford U.)].

The number of staves and the tilt angle between them in the azimuthal direction in each layer is different, optimized based on the coverage requirements and by the radius of the layer. Table 1 shows the radius of the layers optimized to allow sufficient space during installation while ensuring sufficient overlap between the modules of adjacent staves for alignment purposes and hermeticity. The later sections will outline how this requirement of module proximity between adjacent staves poses a huge challenge to module mounting.

The inherent chirality of the system gives space for quite a number of combinations one can make in the staves. The inner two layers have short strip modules, and the outer two have long strip. Staves in side 'C' have the EoS master PCB on top with the locking points facing downwards (what this means will become clearer in the next section) because of the way the staves points attach to the global support structure. This, in total gives 8 possible combinations of stave types. The procedure for assembling different types is different and needs to be properly adjusted for.

Barrel Layer	Type	Number of Staves	Radius [mm]	$ z $ [mm]	Tilt Angle [degrees]
0	Short Strip	28	399	0-1372	13
1	Short Strip	40	562	0-1372	12
2	Long Strip	56	762	0-1372	12
3	Long Strip	72	1000	0-1372	11

Table 1: Radius, extent in the z direction, and tilt angle for ITk strip barrel layers [3].

3 Local Support Structure

A *stave* is an assembled detector unit consisting of many sub parts-

1. carbon foam based local support structure called the stave core,
2. 28 electrical silicon strip modules (either short strip or long strip),
3. EoS PCB cards on both sides of the stave (either master or slave),
4. and wirebonds providing electrical connectivity.

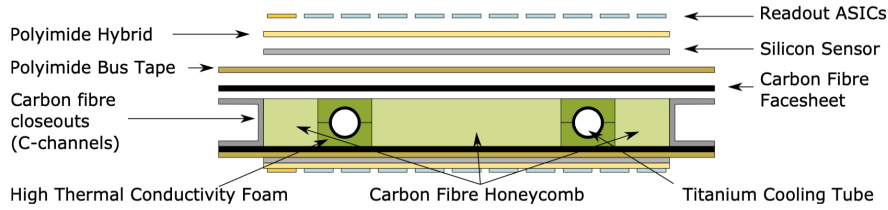


Figure 5: Schematic of the internal structure of the stave core, with the silicon sensors and ASICs added [2].

Figure 5 shows the different layers of a fully assembled stave in top view and side view. The bulk of the stave core is made out of carbon fibre honeycomb with closeouts made of carbon fibre lining the edges. A titanium cooling tube runs through the bulk serving as a thermal reservoir. A polyimide bus tape is co-cured on both the sides of the stave core which provides a medium for electrical connectivity throughout via copper channels.

The EoS cards are attached to high z ends of the stave. The copper channels running throughout the stave core provide electrical connectivity between the individual modules EOS components. Figure 6 shows a mounted EOS master card on a partially assembled stave.

3.1 Locking Points

Locking points are injected moulded elements made of a plastic masterial called Ultem. Five of them attach to the stave core placed with a tolerance of $100\ \mu m$ in the z direction and $r - \phi$ direction (except the corner-most one, which is placed with a



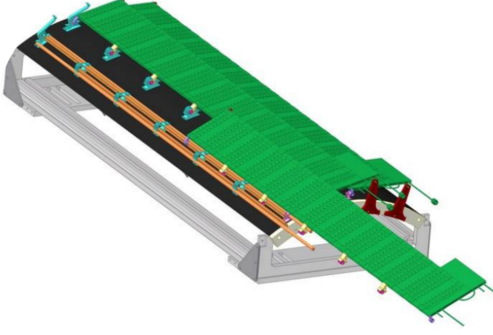
Figure 6: High z corner of a stave core with the End of Substructure master card glued down. Wirebonds connect the copper channels on the bus tape to the electrical components on the EOS. Titanium loops running through the stave core open and close on the same edge. Also shown is glue put down on the core right before electric modules are placed down.

precision of $50\ \mu\text{m}$ in the z direction, the reason for which will become clearer in the later sections).

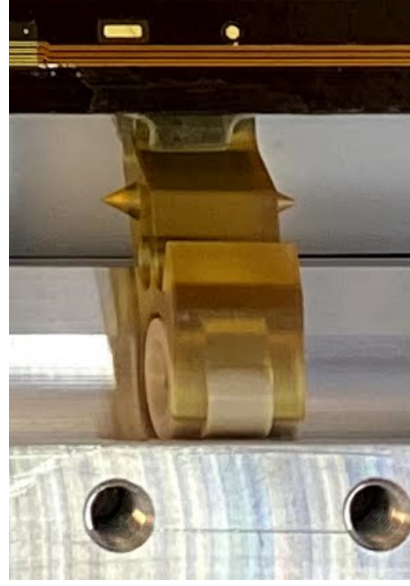
The locking points serve a dual purpose - provide structural support to the staves, and serve as calibration references for module placement. Figure 7a shows a stave being inserted in the global support of the ITk which is held in place using the five locking points attached to the stave. Figure 7b shows a locking point attached to a stave core with precision cones on either sides of it. Before putting down electrical modules, a camera measures the position of the tips of the cones and creates an imaginary line which serves as the longitudinal axis of the stave. The modules are hence placed in reference to this line.

3.2 Bus-tape

On both sides of the stave core are face-sheets formed from layers of high-modulus unidirectional carbon fibre material with pre-impregnated radiation tolerance, and cyanate resins together with a copper/polyimide bus-tape. The bus tapes facilitate the high frequency and bandwidth data transfer the strip detectors are designed for. Also contained are the channels to facilitate slow controls to the module electronics, and the high voltage supply required to deplete the Silicon inside the sensors.



(a) The stave being installed into the global support. The contact points are the locking points on the stave core [2]



(b) Zoomed in top view of a locking point with high precision cones on the sides.

Figure 7: Locking points serve a dual purpose for stave assembly and integration.

To provide a landing for the wirebonds, the uppermost surface of the bus tape contains bond pads which directly connect to the copper traces under the polyimide surface. A set of such bond pads show up repetitively, once for every module. The positioning of these bond pads with respect to the locking points, which, as shown above, provide the reference system for the module placement, is a critical specification and needs to be strictly managed. Extreme distortion of the bus tape can make the wirebonding extremely difficult and even impossible if the distortion is out of specification.

Figure 8 shows the master side of a C type stave core. For all purposes henceforth, this side of the stave will be referred to as side J (since the stave looks like the character J with the EOS on top left), and the other side will be referred to as side L.

While there are multiple configurations for a stave possible, as laid out in the previous section, the bus tape is designed to have just two possible configurations, left handed and right handed. Figure 9 shows them. For the staves placed on the A side of the ATLAS experiment, the top face has a RH bus tape while the bottom has a LH bus tape, and vice versa for the staves placed on the C side.



Figure 8: Top view of master side of a C type stave core at BNL.

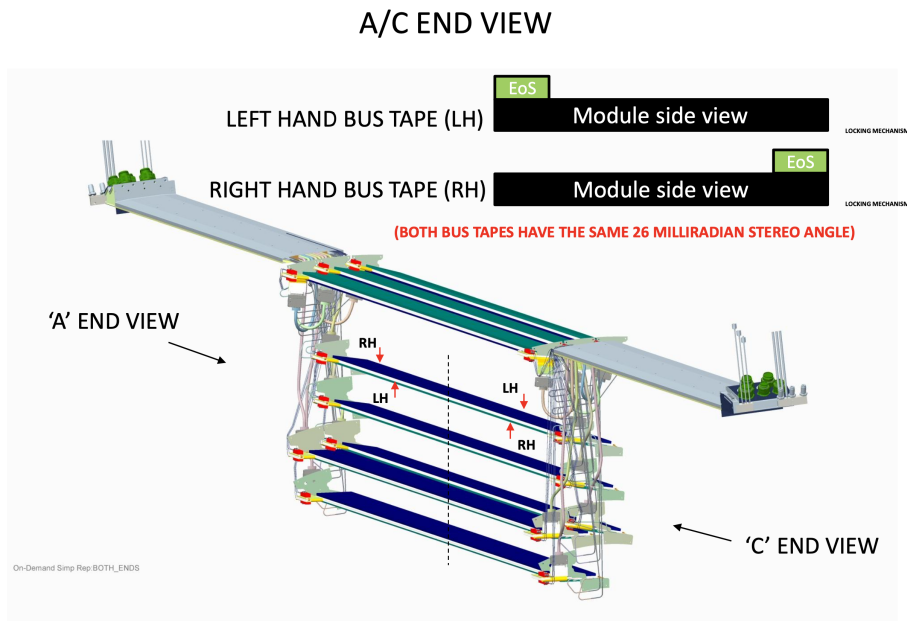


Figure 9: Schematic showing left handed (LH) and right handed (RH) bus tapes as placed inside the ATLAS experiment [Source - Tony Weidberg (Oxford U.)].

4 Stave Assembly

This section will describe the procedures of assembling a stave at Brookhaven National Laboratory. Figure 10 shows the module mounting setup. The stave core is placed in an Aluminum assembly frame roughly aligned using pins. An XYZ stage with an arm has a precision on $1\text{ }\mu\text{m}$ and a range enough to go over the whole core. Attached to the arm are a 10 MegaPixel camera (which roughly translates to $\sim 2\text{ }\mu\text{m}$ per pixel), an auger valve glue dispenser, and a high precision laser used for out of plane metrology. The computer set next to the assembly station operates the setup using the appropriate controllers.

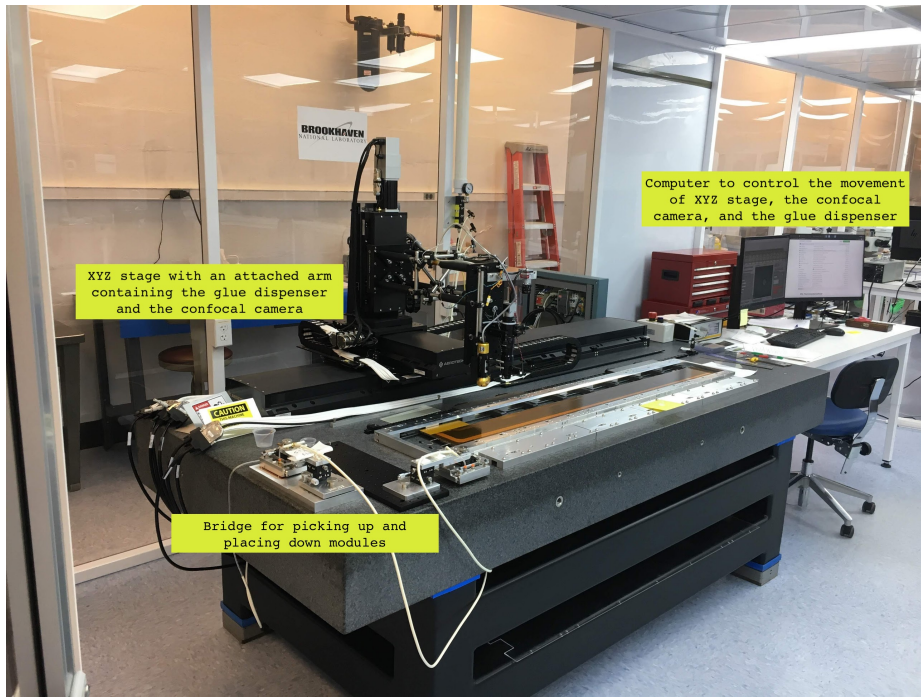
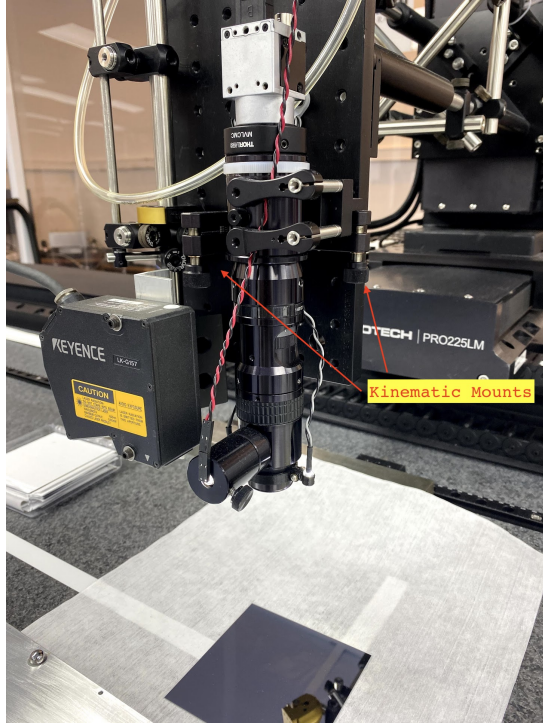


Figure 10: The stave assembly setup at BNL consists of an XYZ stage set atop a granite platform.

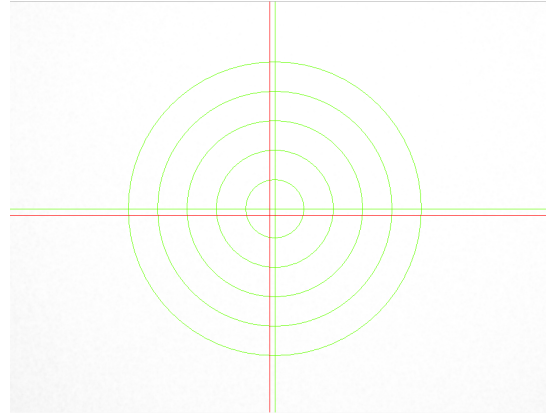
Module mounting can be broken down into three rough stages - calibration, coordinate system building, and module positioning.

Calibration

The calibration step consists of preparing the system for accurate measurements. This includes aligning the optical axis to reflect true movements in vertical directions, and



(a) Camera used to identify locking points and fiducial markers on modules, attached to an optical bread board via kinematic mounts.



(b) Vignetting analysis graphical output for a misaligned optical axis. The kinematic mounts are adjusted until the centre of the two circles (red and green) coincide with each other.

Figure 11: Setup used for vignetting analysis for optical alignment, and the corresponding graphical output.

not accidentally measuring angled distances. The camera's vignette allows the user to assess the optical axis' alignment quality, since the camera uses coaxial light as its primary illumination source. The coaxial light travels the same optical path as it passes out of the optics and reflects off of a piece of test silicon, lying flat on the granite table surface. An aligned axis, perpendicular to the test silicon surface, shows a symmetric, centred vignette. Figure 11 shows the camera setup used to align the optical axis and a representative unaligned vignetting output.

The second step to calibration is determining the pixels to micron ratio, as well as the focal height. It is important to be able to get an accurate value of this parameter so that the stage movement can work in coherence with the feedback from the camera. This is done using a strip module. The strips are designed to be separated by a distance of $75.5 \mu\text{m}$ for both long strip and short strip modules. The camera runs an intensity profile over the strips at different heights. The number of pixels between two strips (which is the separation between two dips in intensity) is then

Reference Coordinate System

Figure 12: Locking points serve a dual purpose for stave assembly and integration.

16

Module Placement

Modules are placed at a stereo angle of 26 mrad with respect to the stave centreline to maximise overlap between consecutive layers of electrical modules. The module location is identified by high precision fiducial markers placed at each corner of the sensor. The nominal locations of these fiducial marks are determined using the reference system, using which the modules are placed.

After calibration, and alignment, the index of the module that is to be mounted (0-13) is chosen, and the XYZ stage is asked to move to one of the corners (ABCD, starting from bottom left and going anti-clockwise). The camera matches the view-point in real time against a template of the fiducial markers to determine the offset from the nominal, which helps the technician correctly align the corner. Figure 13 shows the pattern match of a corner fiducial happening in real time in a LabVIEW based software.

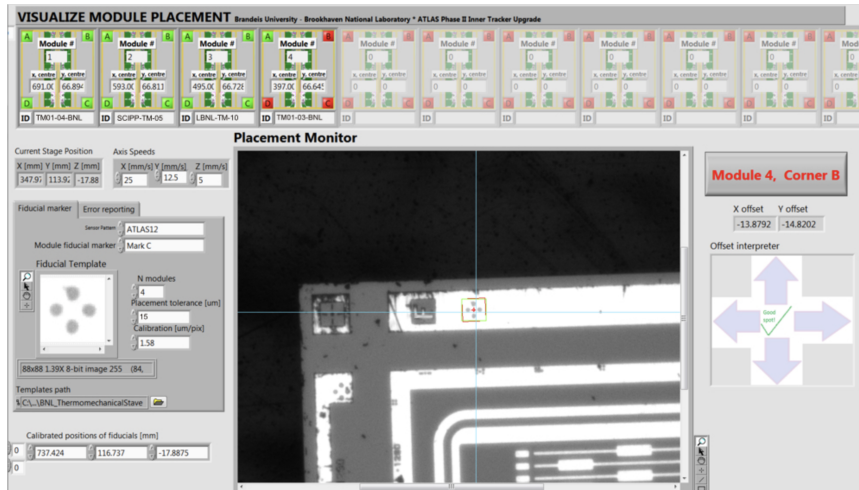
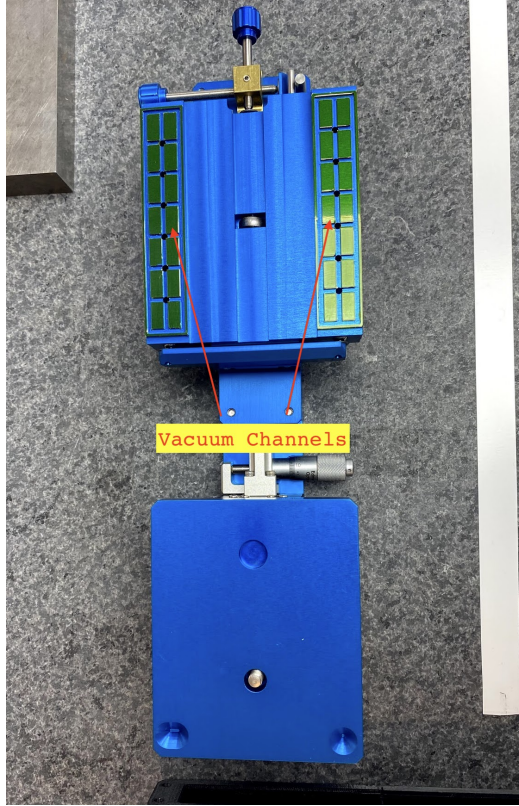
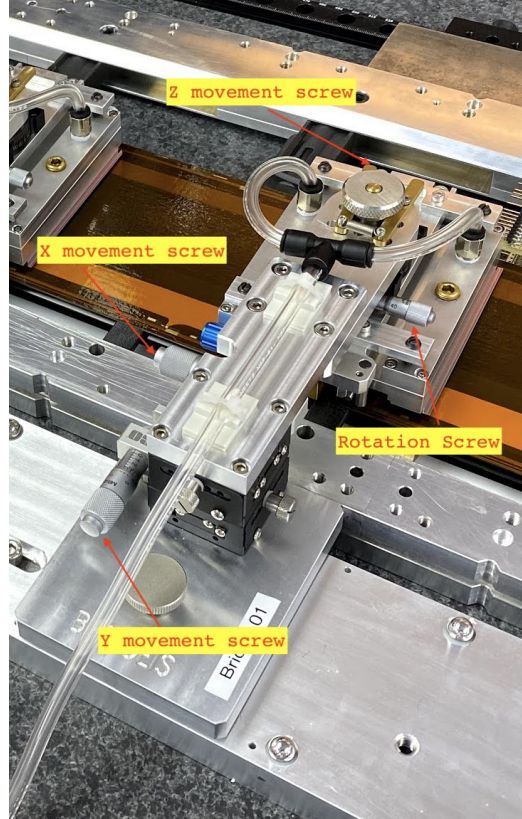


Figure 13: The LabVIEW based software pattern matches the fiducial markers in real time used to align the module at the right positions with a 26mrad stereo angle.

A module is then picked up using a tool which has vacuum channels on either sides to ensure minimal movement. Figure 14a shows the bottom of a short strip module pickup tool. Four sets of screws available on the pickup tool control the movement of the 3 stages - three for in plane motion and one for vertical movement of the module. The technician uses the first three to properly align the module, two for X-Y movement and one for rotation. See figure 14b showing the top view of the tool with a module underneath. After a dry placement, the module is moved to the side and glue is laid down on the stave core surface at predetermined positions. Figure 6 shows the glue pattern used for long strip modules. The glue, SE4445, is a polymeric mix of two liquids with an expected setting time of 5 hours.



(a) Bottom view of a short strip module pickup tool with vacuum channels used for alignment while mounting.



(b) Top view of a module pickup tool with screws for movement of the module on the bus tape surface.

Figure 14: Top and bottom view of the module pick up tool used to move and align an electrical module during stave assembly.

The module is then aligned again, after which it is pressed down on the glue using the vertical movement screw. A final alignment is done, and then the setup is left untouched overnight for the glue to dry. Figure 15 shows three long strip modules left to dry after the final alignment.

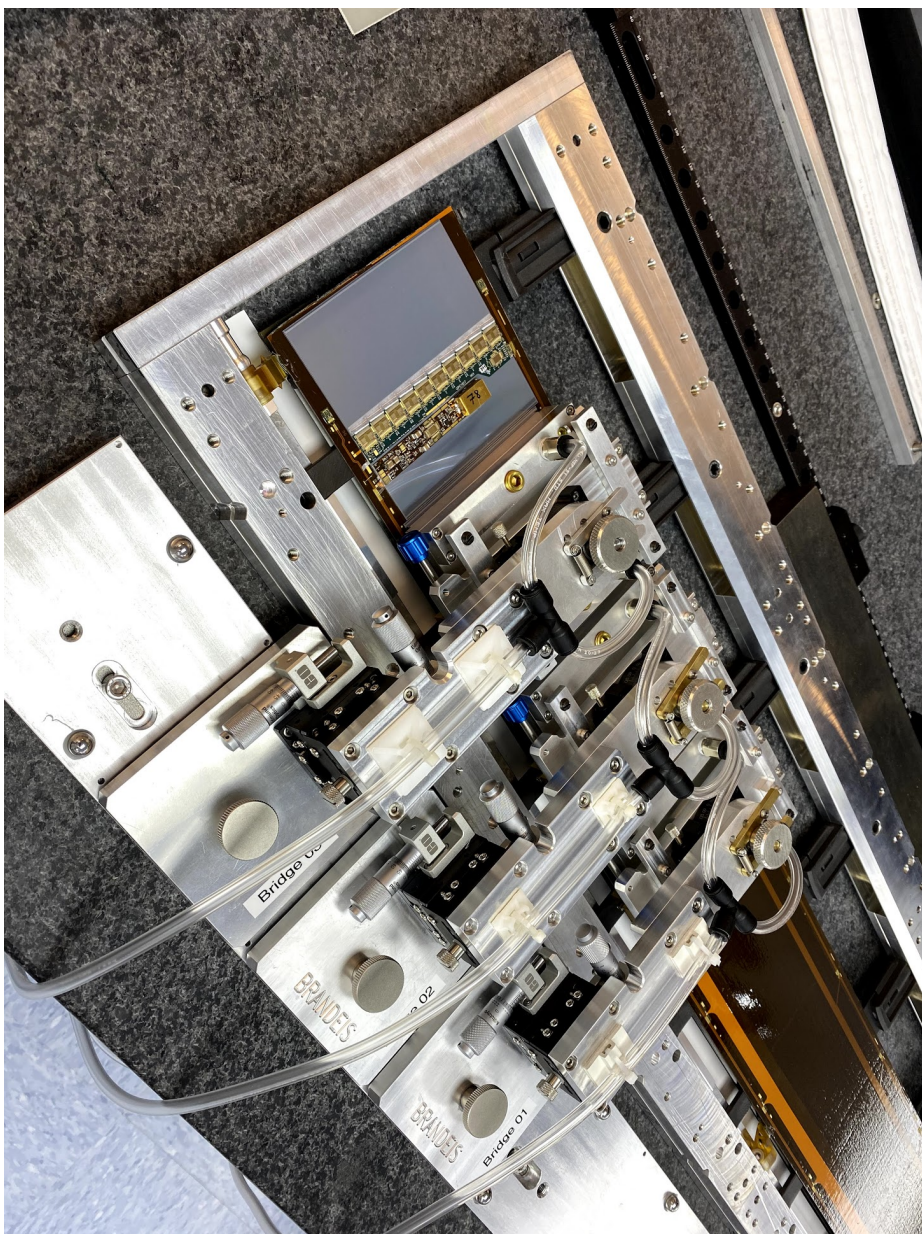


Figure 15: Modules 1-3 drying on the J side of US Stave #1 after the final alignment.

5 Metrology

A part of the stave core manufacturing is the Quality Control protocol. The locking points are measured and it is ensured that the required tolerance is reached. The specifications are based on multiple factors, few of them being the system integration of the staves into the local support as well as to maintain the module placement accuracy, since the modules are put down with reference to the locking points.

As a part of the same Quality Control procedure, the bus tape is surveyed for excessive bow along the $r - \phi$ direction (or like it is called in this section, the y direction) and shrinkage along the z direction (or like it is called in this section, the x direction).

Finally, as a part of the Quality Control step of the module loading procedure, the module fiducial positions are required to be within $100\ \mu m$ of the nominal position.

This section outlines the different types of metrology done at Brookhaven National Lab, and the results from the corresponding measurements. Although the stave core is not manufactured at BNL, the locking points and the bus tape were surveyed anyway to ensure proper measures are taken before mounting the modules according to what was later found to be an out-of-spec stave core. The next section talks about the steps taken to get around unrealistic tolerances which are in principle required to maintain accuracy but very difficult to ensure in a manufacturing lab.

5.1 Locking Point Survey

Three stave cores were surveyed for their locking points during the past 18 months. The first core (which is referred to as US core #1 in this report) was manufactured at the University of Liverpool, UK, and the other two were manufactured at Yale University. Modules were mounted on core #1 which was eventually used to pass the Final Design Review for both stave assembly and stave core manufacturing. Core #2 was damaged during the core assembly step, wherein a copper trace right at the edge of the bus tape was cut off due to excessive bus tape bow. Core #3 is an electrically functional core, however, there are several challenges to overcome during module loading because of the out-of-spec components.

Figure 16 shows the locking point survey results for the three stave cores measured at Brookhaven Lab. The residuals shown are distances of the locking point centres to the best line and the angle shown on the title is the angle of the stave axis

with respect to the lab x -axis.

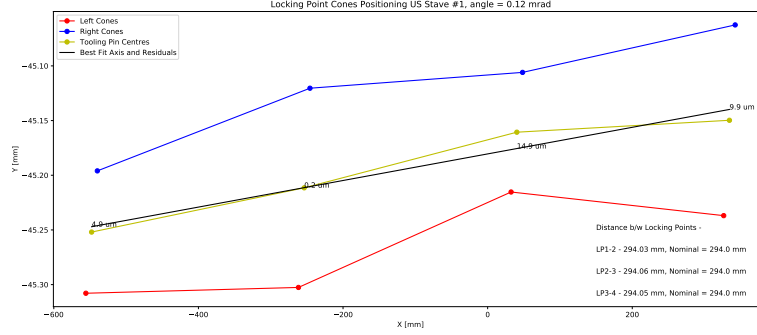
Core #1 had an incorrectly placed LP0, and so it was decided to leave that locking point out for the purpose of module placement. Even though at that time there were no clear specification on the placement of locking points to compare against, the collinearity was deemed good enough for module placement with the worst residual being $15\ \mu m$. It was also determined after extensive studies that the non-zero residuals were a combination of two sets of defects. Firstly, the locking point cones themselves were moulded not to extremely high precision (offset between cone tips as high as $87\ \mu m$) and that lead to non-collinearity of two cones of the same locking point. Secondly, the insertion mechanism of the locking points were found to be improper, leading to an additional degree of error.

Core #2 was the first US manufactured stave core, and the purpose of its survey was to compare manufacturing feasibility against design parameters. While it was decided that the locking point axis will be chosen as the stave core axis by definition, the distance between locking points was still a strict specification, the tolerance on which was set to $200\ \mu m$. The distance between LP0 and LP1 was out-of-spec by $40\ \mu m$, hence failing the requirement. Such a stave core would be **rejected** in production.

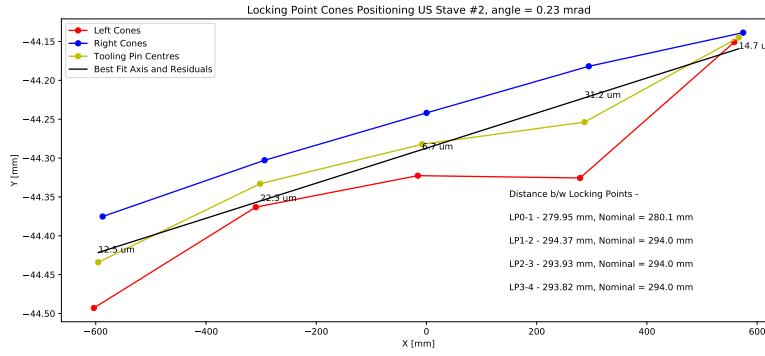
Core #3 is the first electrically feasible stave core manufactured in the US. However, the stave core fails on multiple fronts. The distance between LP0 and LP1, and between LP2 and LP3 fails the $200\ \mu m$ requirement, and as is apparent from the very high residuals, the imperfections in locking point insertion are significant. Because of the limitations of the survey system at BNL, direction measurements on the locking point insertions could not be made. The manufacturing site, however, had independently made better measurements and had reached the same conclusion that the core was unsuitable. Currently, the team is trying to find ways to use this core for module mounting anyway and there has been not a decision yet. Such a stave core would be **rejected** in production.

5.2 Bus Tape Survey

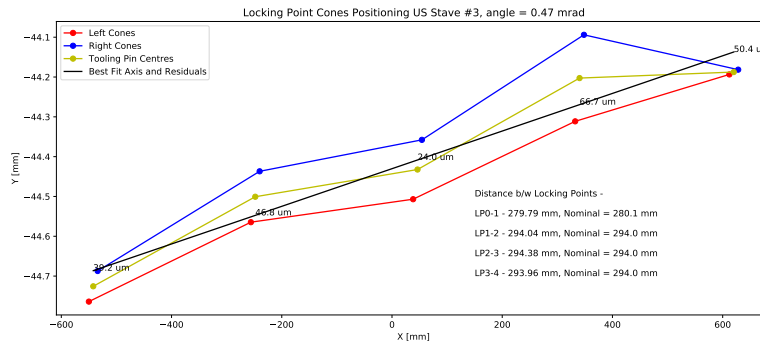
Two stave cores were surveyed for their bus tape, core #1 and core #3. To provide supplemental results, two sets of fiducial as seen on a bus tape are surveyed - the top left corner of the fast return ground bond pad, and the bottom left corner of the high voltage bond pad (see Figure 17). Since every module needs to have these bond



(a) Locking point survey for US stave core #1. Locking Point 0 was dropped from the survey since it was placed incorrectly.



(b) Locking point survey for US stave core #2.



(c) Locking point survey for US stave core #3.

Figure 16: Locking Point survey results for the first three stave cores measured at BNL since 2019. The cores were laid down on J side with the rightmost locking point (LP0) closest to the $z=0$ end, and the leftmost locking point (LP4) at the high z end.

pads, they are placed at a same period as the modules are, at a nominal distance of 98 mm consecutively.



Figure 17: A number of bond pads repeat themselves 14 times over the length of the stave with the a gap of 98mm between them. Two bond pads which are used for the survey in this section are highlighted - the high voltage supply pad and the fast return ground pad.

Figures 18 and 19 show the results from the bus tape survey.

The tolerance on the contraction is set to be at $\pm 1\text{mm/m}$. Over a length of $\sim 1.4\text{m}$ of the bus tape, this comes out to be $\pm 1.4\text{mm}$. The tolerance on the Y positions of the bond pads is set to be at $\pm 300\mu\text{m}$.

Table 2 summarizes the bus tape metrology results for stave cores #1 and #3. The values are true to hundredth of a millimetre limited by user error and camera precision. The bow is measured as the distance between the highest point and the lowest point in the lab frame, within negative values signifying the bow is towards the

bottom half and positive values signifying the bow is towards the top half. Bow values shown are in lab frame and the rotation adjusted values are significantly shorter.

	Stave Core # 1		Stave Core # 3	
	Side J	Side L	Side J	Side L
Shrinkage (mm)	1.07	1.64	1.34	1.81
Bow (μm)	-290	290	-700	350

Table 2: The shrinkage and bow for Side J and Side L for stave cores #1 and #3. The bow values are in lab frame. All numbers shown are accurate to $10\mu\text{m}$. The values shown in boldface are out of specification.

Core #1 Side J Both contraction and shrinkage are within tolerance.

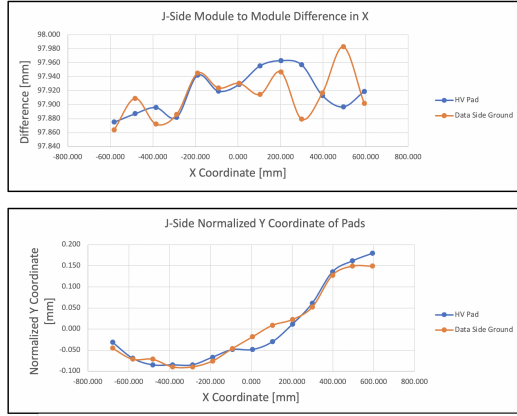
Core #1 Side L Bow is within tolerance but shrinkage is out-of-spec. Wirebonding on this side was a challenge since the bonds had to be made longer than usual. It was decided that the module will be shifted by 1.6mm towards the EOS so that the wirebond lengths become progressively shorter from the $z = 0$ edge to the high z edge. This bus tape would be **rejected** in production.

Core #3 Side J Shrinkage is within tolerance but bow is out-of-spec. Such a large value of bow ($\sim 300\mu\text{m}$ in stave frame) is expected to create wirebonding issues. It is still being decided as to how to tackle this issue. This bus tape would be **rejected** in production.

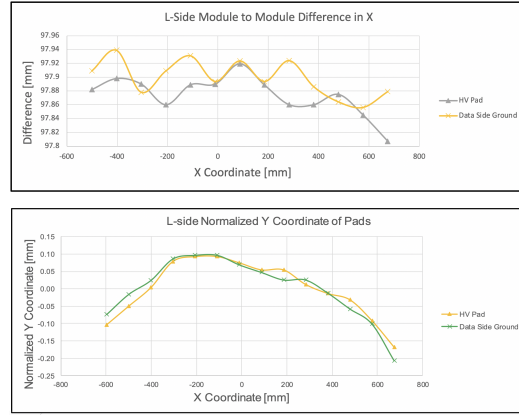
Core #3 Side L Bow is within tolerance but shrinkage is out-of-spec. The shrinkage value being extremely far off nominal is expected to create severe wirebonding issues. It is still being decided as to how to tackle this issue. This bus tape would be **rejected** in production.

5.3 Module Metrology

As a part of the quality control step of stave assembly, the module placement has to be surveyed in all three directions, in plane and out of plane. The in plane measurement uses the same camera as is used during module placement. The out-of-plane measurement is made using a laser based device. While the first long strip stave was assembled at BNL, the out of plane metrology facility was still being worked on and hence there are no results on the actual stave to substantiate the claims that will be made hereon, but some dry tests were done using bare electrical modules to establish

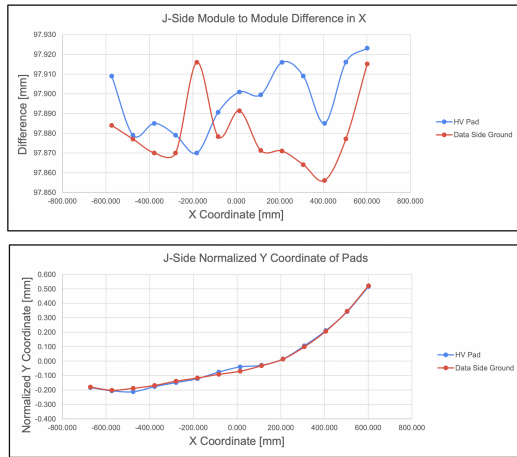


(a) Bus tape survey for Side J. The top plot shows the X coordinate difference between consecutive fiducial markers. The bottom plot shows the normalized Y coordinate of the fiducial markers.

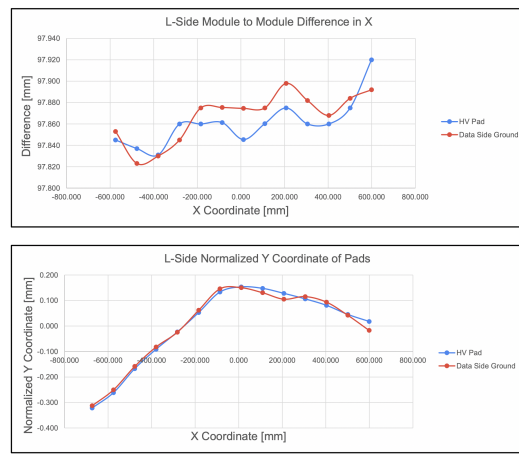


(b) Bus tape survey for Side L. The top plot shows the X coordinate difference between consecutive fiducial markers. The bottom plot shows the normalized Y coordinate of the fiducial markers.

Figure 18: Bus tape survey for US Core #1. Two fiducial markers per module vicinity are measured, the high voltage bond pad (HV Pad) on the bottom half of the bus tape, and the fast signal return pad (Data Side Ground) on the top half of bus tape.



(a) Bus tape survey for Side J. The top plot shows the X coordinate difference between consecutive fiducial markers. The bottom plot shows the normalized Y coordinate of the fiducial markers.



(b) Bus tape survey for Side L. The top plot shows the X coordinate difference between consecutive fiducial markers. The bottom plot shows the normalized Y coordinate of the fiducial markers.

Figure 19: Bus tape survey for US Core #3. Two fiducial markers per module vicinity are measured, the high voltage bond pad (HV Pad) on the bottom half of the bus tape, and the fast signal return pad (Data Side Ground) on the top half of bus tape.

proof of principle. Figure 20 shows the oblique view of the fully assembled master side of the stave which was measured. The in-plane metrology for the first 28 module long strip electrical stave was done and the results are shown.

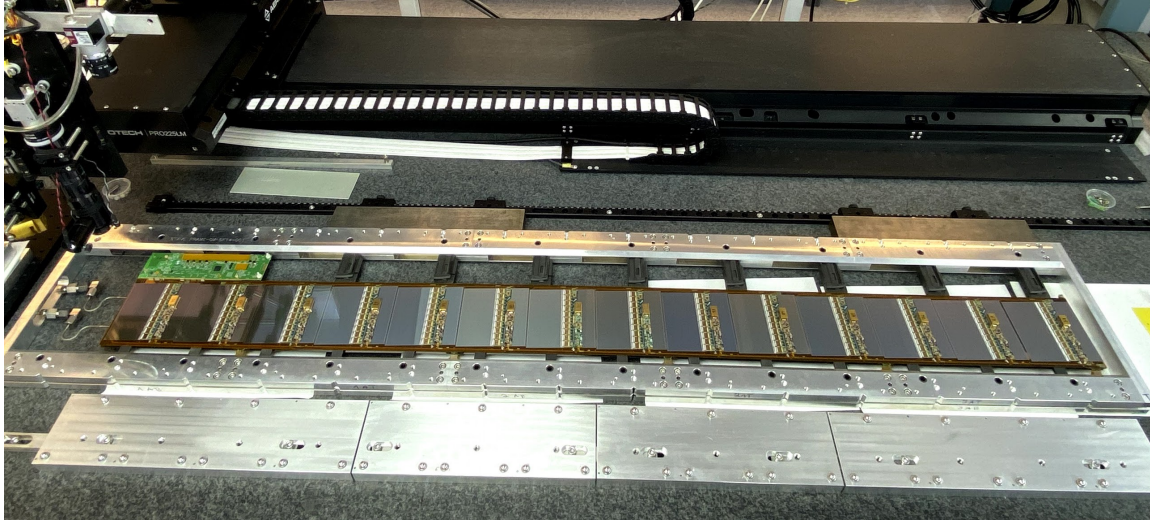


Figure 20: Top view of the master side of the long strip stave assembled at BNL.

Module In-Plane Metrology

For the in plane metrology, the corner fiducial marks of the modules have to be measured thrice - once after they are glued down, once right before the mounting bridge is removed and the glue has dried, and lastly after the bridge has been removed and the module is firm in place. Fundamentally these numbers should not be significantly different from each other because the system is not disturbed throughout the process apart from nominal changes environmental factors, such as ambient room temperature.

The trend of module movement over the three different stages is mainly used for debugging purposes to try and understand where and what went wrong. The final displacement of the modules as compared to their nominal positions is a strictly controlled measurement which, if not properly enforced, can lead to two neighboring modules coming in mechanical or electrical contact or hang over the stave edge. Any of these conditions will render a stave unusable in production. Figure 21 shows the movement of the four fiducial markers on module 1 of Side J at three different stages of mounting. The movement is negligible for all purposes.

Figures 22 and 23 shows the in-plane metrology results for Side J and Side L respectively. Three different mounting bridges were used to mount modules throughout

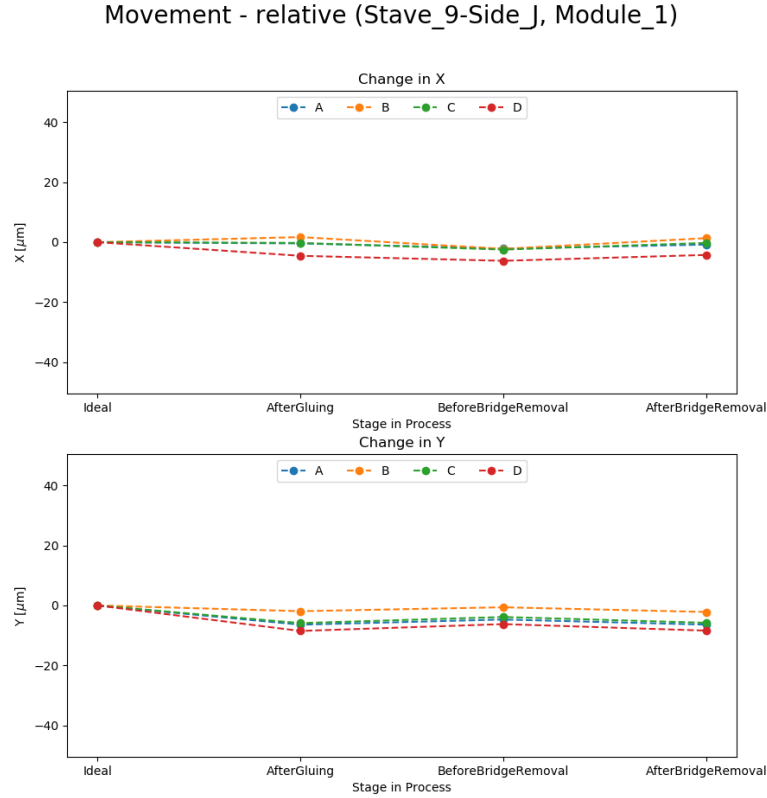


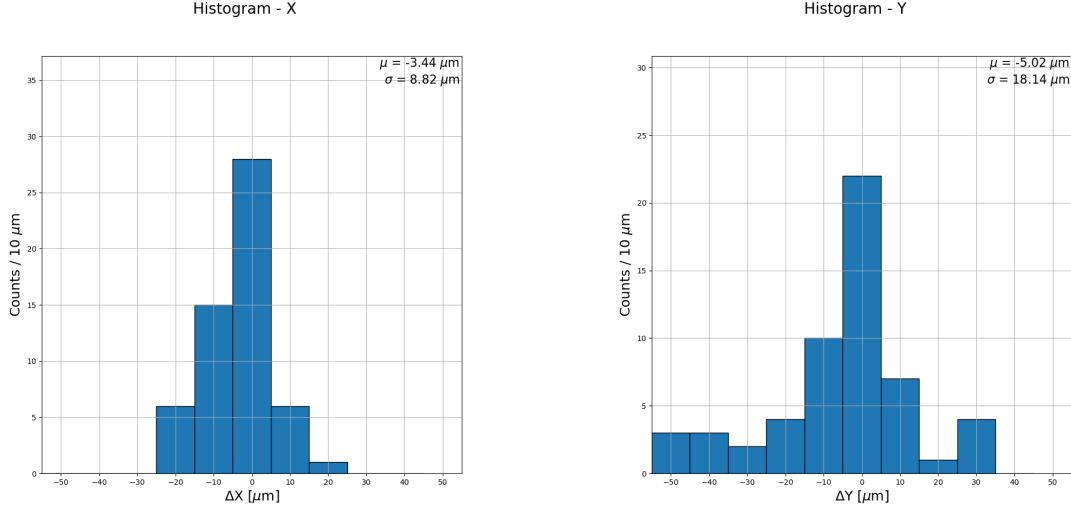
Figure 21: Movement of the module corner fiducial markers for module 1 of Side J of US Core #1 at different stages of mounting.

the process and there were no out-of-spec placements. This feat was timely achieved for the module loading process to pass the Final Design Review.

Module Out-of-Plane Metrology

The module out-of-plane measurements are made using a laser based device. Figure 24a shows the laser mounted on the XYZ stage arm which projects an oblong spot of the size $1.7 \text{ mm} \times 120 \mu\text{m}$. Figure 24b shows the method on which the laser works. The triangulation method uses the final position of the received scattered laser spot to a calibrated value of the corresponding height. The accuracy and precision of the laser system was determined to be less than a $1 \mu\text{m}$, which is much better than the target precision of $10 \mu\text{m}$.

The strips on a module can be oriented in two different ways, and so can the



(a) Histogram of deviation in X positions of all 4 corners of 14 modules.

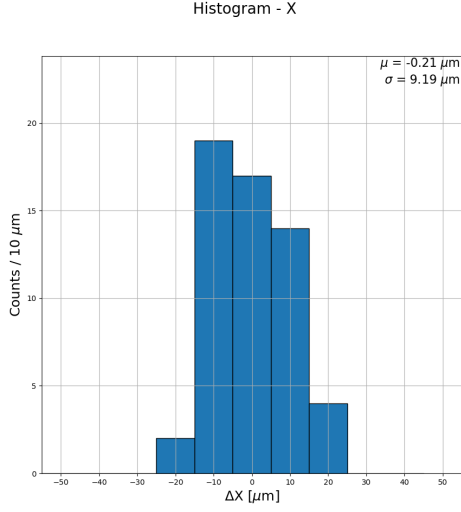
(b) Histogram of deviation in Y positions of all 4 corners of 14 modules.

Figure 22: Histograms of deviation in positions of all four corners of the 14 modules mounted on Side J of US Stave #1. The deviation is taken as the difference in position after the mounting bridge is removed to the nominal position obtained by referencing the locking points.

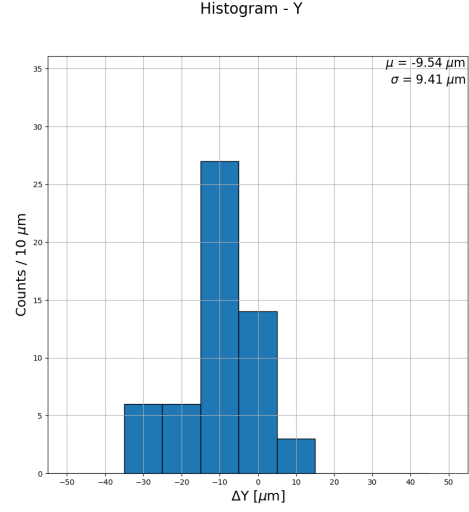
major axis of the laser spot. This gives four ways in which the height profiling can take place. It was determined that the method that works best is when the strips and the major axis of the laser spot are perpendicular to each other so that the reflected light shows a height averaged over a number of strips, hence giving a more accurate result. Figure 25 shows the height profile taken on a mechanical ATLAS17LS sensor placed on a granite surface. The sensor height was measured to be approximately 400 μm , which is the expected value.

A test metrology was done on an unmounted electrical module to test proof of principle. A total of 90 points were measured on the module with reference to a point on the PCB on the test frame. Figure 26a shows the rough location of points where the heights were measured and figure 26b shows the results from the survey. The lowest point is 290 μm above reference, right next to the hybrid, and the highest point is 471 μm above reference at one of the corners. The approximate bow of the module is hence $\sim 200\mu m$, which is nominally expected.

The metrology done on a module placed in a test frame does not represent the true shape of the module since the object is not free from external forces. There are suction cups at all four corners of the module keeping it in place, which also deform it. However, the metrology predicts correctly the approximate profile of the module



(a) Histogram of deviation in X positions of all 4 corners of 14 modules.



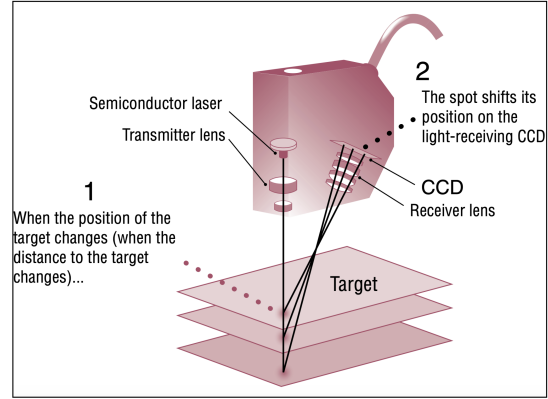
(b) Histogram of deviation in Y positions of all 4 corners of 14 modules.

Figure 23: Histograms of deviation in positions of all four corners of the 14 modules mounted on Side L of US Stave #1. The deviation is taken as the difference in position after the mounting bridge is removed to the nominal position obtained by referencing the locking points.

as one would expect a paraboloid under the constraints given.



(a) A laser source LK-G157 is used to measure heights of modules for the out-of-plane metrology.



(b) The height measurement uses the triangulation method. A semiconductor laser projects an oblong laser spot and measures the spot of the scattered light.

Figure 24: The height measurement laser used at BNL and the working principle used by it.

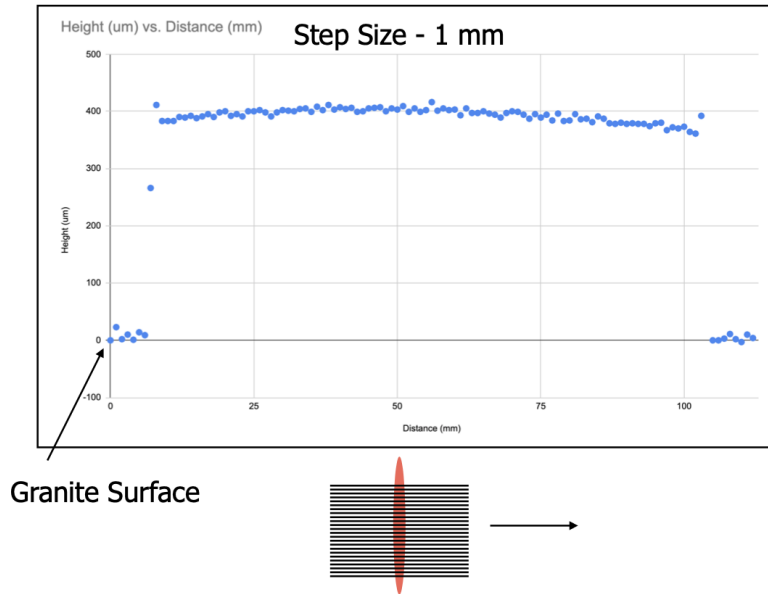
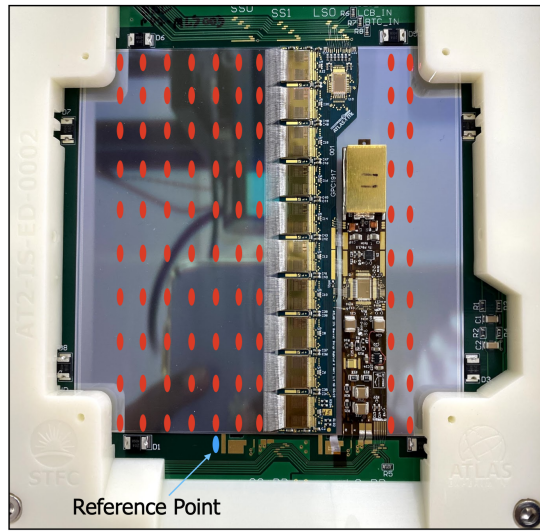
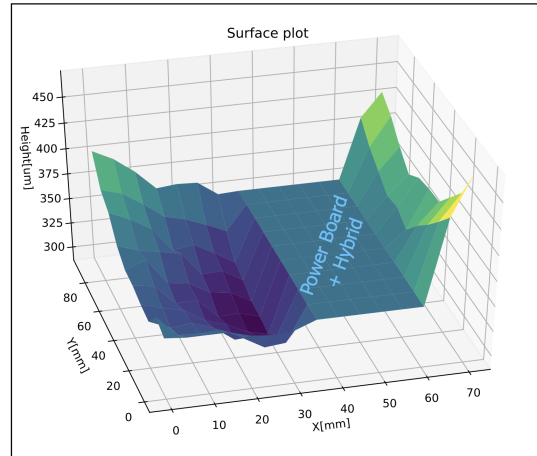


Figure 25: The height profile of an ATLAS17LS sensor taken using the LK-G157 laser. The laser spot was oriented perpendicular to the strips on the silicon sensor, while the stage was moved along the strips in steps of 1 mm. The average height was approximately $400\text{ }\mu\text{m}$, with an overall convex bow shape.



(a) The red spots show the rough positions of the measurement locations. The cyan spot shows the point of reference representing zero height.



(b) 3D Plot of the measured height on the module. The lowest point is $290\mu\text{m}$ above reference and the highest point is $471\mu\text{m}$ above reference.

Figure 26: Out-of-plane metrology done on an unmounted long strip electrical module using 90 points.

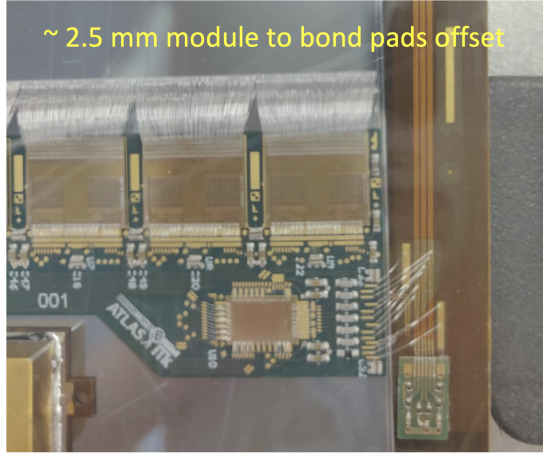
6 Drawing Updates

Building a 28 module stave for the first time brought on its own sets of challenges at every stage - metrology, alignment, and mounting. The locking points with a set of cones are used for alignment for the first time ever. The injection moulded objects are made to be of extremely high quality to be properly recognized by the camera in use, and their insertion into the stave core bulk has to be high-precision so the reference system build does not give significant offsets to the modules. The module closest to $z=0$ is $73\text{ }\mu\text{m}$ away from the edge. The module to module gap is $346\text{ }\mu\text{m}$. This would mean that an inaccuracy in the positioning of the locking points giving rise to an overall offset of even $50\text{ }\mu\text{m}$ could very well lead to electrical failures due to sharp voltage drops of the order of 500 V in neighboring on and off modules. Improvements in the engineering drawings have since been made to fully account for such possibilities, and work is still ongoing to improve them further. This section briefly outlines the progress that has been made since 2019.

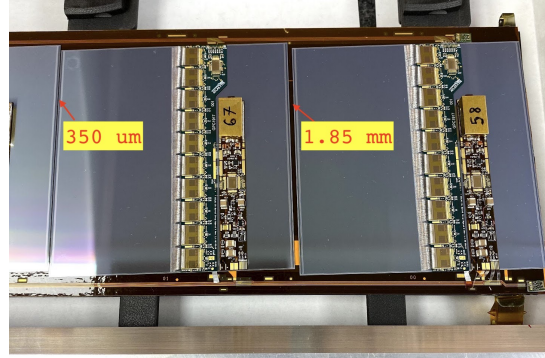
6.1 Bus Tape Design Changes

The first module (module 0) was placed down on Side J of stave core #1. The locking points were surveyed and it was determined that after dropping LP0, the offset on modules placed would be insignificant because of the low residual values of the locking point cones. Although the module was successfully placed down according to the drawings, it was determined that the module was approximately 2.5 mm away from the bond pads, as was noticed from the extremely long length of the wirebonds. Figure 27a shows the wirebonds made from module 0 to the bus tape, which are unnaturally long. It was determined after a bus tape survey that while there was a 1.1 mm shrinkage in the bus tape which accounted for part of the offset in the module 0 positioning, there was an additional 1.5 mm placement offset in the bus tape drawings but not in the stave core drawings. Both these sources accounted for the total 2.5 mm error.

A tighter specification was then added on the amount of shrinkage of the bus tape which happens post the co-cure process, as is laid out in the previous section. A decision was taken to move all the modules away from the $z=0$ end by 1.5 mm to be in range of the bond pads, and the drawing has been amended to account for this. Figure 27b shows a larger gap between modules 0 and 1 than between modules 1 and 2, which arises as an outcome of adding an additional 1.5 mm offset to all the modules except module 0.



(a) Strained wirebonds made on the data side for Module 0 Side J of US Stave #1.



(b) Modules 0, 1, and part of 2 on Side J of US Stave #1. The gap between modules 0 and 1 is 1.85 mm whereas the gap between modules 1 and 2 is the nominal value, 346 μm .

Figure 27: Out-of-plane metrology done on an unmounted long strip electrical module using 90 points.

The first stave core built in the U.S. with cones on locking points was core #2. While the co-curing was done successfully, the bow of the bus tape caused the edge of a conductive surface inside the bus tape to go outside of the stave core bulk area and was accidentally cut off while the core was being made. Several attempts at making the bus tape showed that it was extremely difficult to control the bow of the bus tape within the specifications, hence a decision was made to increase the width of the stave core by 1 mm, in addition to slightly relaxing the tolerance on the bow, as is outlined in the previous section.

6.2 Stave Core Tolerance Changes

It was decided to drop LP0 from Stave Core #1 while defining the coordinate system for module mounting. In production, however, something like this cannot be done stave-by-stave and all cores will need to adhere to strict tolerance requirements, now dictated by module positioning requirements. The multiple sets of metrology done on the locking points showed that purely relying on them for placement was not a good idea in the long term, and that the modules should in some way be referenced to the closeout edge, so that module 0 does not hang over the edge in an extreme case.

A few studies were done to check the feasibility of referencing the closeout edge to position the modules. However, it was determined to be an unreliable approach because of the rough quality of the edge surface and difficulties in identification.

Hence, it was decided to instead use the locking point axis as a datum and references were added with respect to it.

While earlier LP0 was used as a universal reference to mount the modules, now, the axis formed by the cones translated along the local Y-axis by 64.4mm will provide the stave centreline, and the outer surface of the locking point, which is now strictly specified, will form the orthogonal axis. The intersection of the two datum will be used as a reference to plot the modules. Figure 28 shows the side of the stave core design, with specifications and tolerances mentioned with respect to the locking point axis.

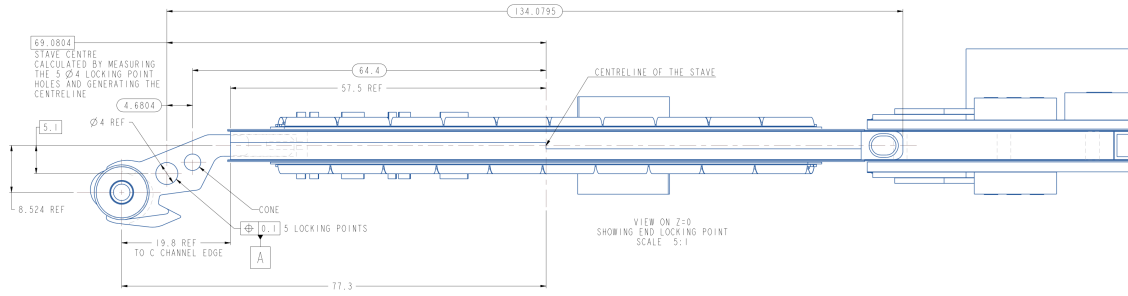


Figure 28: Side view drawing of the stave core. Datum A represents the axis formed by the locking points, translating which by 69.0804 m gives the stave midline. The intersection of the plane $z=0$ with the centreline of the stave is used as a reference to place modules.

7 Conclusion

Over the past two years, BNL has successfully assembled a 28 module long strip stave with a module placement precision of $50\text{ }\mu\text{m}$. With the same setup, two more sets of metrology were done, one of the stave core, and one of the locking points. While the results from the metrology have shown mixed outcomes in terms of breaching the tolerances, the engineering drawings are being modified to account for manufacturing difficulties and at the same time working with a new set of datum which guarantee proper placement of modules.

The module metrology process, which is BNL's responsibility as a part of stave assembly Quality Assurance / Quality Control process, has shown extremely positive results with no module being out of bounds in the first fully mounted stave. The out-of-plane metrology system has an established proof of principle and properly described procedures, with results from measuring a 28 module stave coming in the next few months.

References

- [1] The High-Luminosity LHC Project. 298th Meeting of Scientific Policy Committee. Technical Report CERN/SPC/1068. CERN/FC/6014. CERN/3255, Jun 2016.
- [2] Technical Design Report for the ATLAS Inner Tracker Strip Detector. Technical Report CERN-LHCC-2017-005. ATLAS-TDR-025, CERN, Geneva, Apr 2017.
- [3] Expected Tracking Performance of the ATLAS Inner Tracker at the HL-LHC. Technical Report ATL-PHYS-PUB-2019-014, CERN, Geneva, Mar 2019.