Evaluation of Complex Thermo-Mechanical Structures for High Energy Physics Tracking Application via the Construction of a Novel Thermal Isolation Test Box

A Capstone Project Submitted in Partial Fulfillment of the Requirements of the Renée Crown University Honors Program at Syracuse University

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Abstract

The Standard Model of Particle Physics is briefly described as the physics background to the main thrust of my Capstone Project. The project involved the design, construction, and validation of a thermally isolating experiment case, the purpose of which is to test the main component of the UT detector being constructed for the LHCb Experiment Upgrade program at CERN. The details of the design are presented first, along with the techniques developed for its construction next, and lastly the results of our initial validation assessments.

Executive Summary

For my capstone, I have designed, fabricated, assembled, modified, tested, utilized, and evaluated a large insulating box made of ¼”-thick polycarbonate panels (a strong and transparent thermoplastic laminate material, similar to plexiglass) that is meant to thermally isolate a thin, long, flat carbon fiber structure (with dimensions: 4mm x 1300mm x 97.5mm).

The structure is a prototype design for supporting high-precision sensor equipment that will be integrated into the Large Hadron Collider (specifically, the LHCb experiment). Our previous cooling equipment arrangement is not powerful and the humidity of the lab air can condense on the chilled piping and lead to ice covering much of the sensitive temperature readout equipment when testing a stave, so insulation is necessary to quicken the cooldown rate and eases the strain on the cooling system to hold a structure prototype (hereon referred to as a stave) at the desired temperature and to prevent icing from occurring. During testing, the stave must not warp, bend, or twist in order to meet the LHCb’s mechanical requirements, first while the sensors are being operated and in an ideal environment (<-25°C), second while the sensors are not in operation and resting at room temperature (25°C), and third while transferring from one of those environments to the other. If the staves were to exhibit any extent of unwanted thermo-mechanical behavior (no more than 10μm displacement) during any of those times then the calibrated sensors’ relative positions could be off of their measured positions, rendering useless any attempted measurements. Further, the wire bonds between the sensor panels and the data collection hardware is very delicate (simply a strong breath could break them), so if the stave does not remain rigid then some of the electronic contacts could be broken. Therefore, we

are interested in measuring the physical displacement behavior of many points on the surface of the stave at varying controlled temperatures to investigate how rigid the staves are.

My capstone insulation box (hereon officially referred to as the Thermal Isolation Experiment Case, or TIEC) is meant to assist with insulating the stave test samples from the lab environment to aid in cooling the sample and prevent icing. It also acts to physically stabilize test samples well enough to allow precise thermo-mechanical measurements of the stave while not stressing the stave and breaking the electronic bonds or restricting its thermo-mechanical behavior. Pairings of the complications faced and the TIEC component solutions include: usual insulator material would be opaque, so polycarbonate was decided on as the main construction component to allow visual monitoring; polycarbonate is too weak to depend on a self-supported case, so I developed an aluminum skeletal structure for supporting the load of the TIEC; epoxy would not be enough to hold polycarbonate panels and aluminum blocks together, so we use ¼-20” threaded screws for handling most of the strain; there were several points of weak support in the original design, so modifications were developed to add strength; the external cooling and electronic thermal sensor equipment needs access to the stave within the TIEC, so ports were fashioned in the side facings for coolant inlet/outlet and wire management; controlled/limited access for the cooling pipes and wires is important to prevent much air exchange, so plugs were made to stopper the side ports not in use; the stave had to have minimal thermal contact with the highly thermally conductive aluminum skeletal support structure, so I came up with a “hanging” support system; the TIEC needed one of the sides to be able to be removed so that the staves could be switched out between tests, therefore handles and handle supports were attached to the TIEC’s external front panels; and lastly we were unconfident with how tall the TIEC was (8ft) with such a small base (2ft x 1ft), so I added clamp arms half way up the rear edges to secure the case to the wall of our lab thus further stabilizing the stave for when we're performing sensitive displacement measurements. As the culmination of 3 years' worth of dedication, the TIEC has been constructed and assembled in its entirety and was found to perform satisfactory for stave testing.

The grand scale of this project is to aid the High-Energy Physics group at SU in their collaborative efforts with LHCb to further humanity's knowledge into the fundamental nature of the universe's composition. LHCb is a dedicated experiment for studying the physics of b quarks, including CP-violation and rare decays, New Physics, and other important phenomena. The staves will be the main component of the subdetector known as Upstream Tracker which will be installed in 2019.

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Chapter 1:
Introduction

In this chapter, we introduce the physics concepts and experimental background that drive my capstone project. We discuss the Standard Model of Particle Physics along with CP violation, an important phenomenon which is a major object of study in particle physics. Lastly, we lead into the LHCb experiment and its rational, along with the need for its upgrade.

1.1 The Standard Model

The composition of the known universe can be viewed in some way as a hierarchy: galaxy clusters, galaxies, solar systems, stars, planets and moons, asteroids, space dust, molecules, and atoms. Atoms were named from the Greek word *atomos*, which means "indivisible," as they were thought to be the fundamental building blocks of the universe. Since about 1910, we have known atoms to actually be divisible into fundamental particles. Some examples include protons, neutrons and electrons. These particles are either elementary, like the electron is, or composite, like protons and neutrons. The latter were also thought at one time to be indivisible and have since been shown to be comprised of elementary particles. In a similar way that atoms compose the Periodic Table of Elements, these indivisible, fundamental particles are described by the "Standard Model" of particle physics.

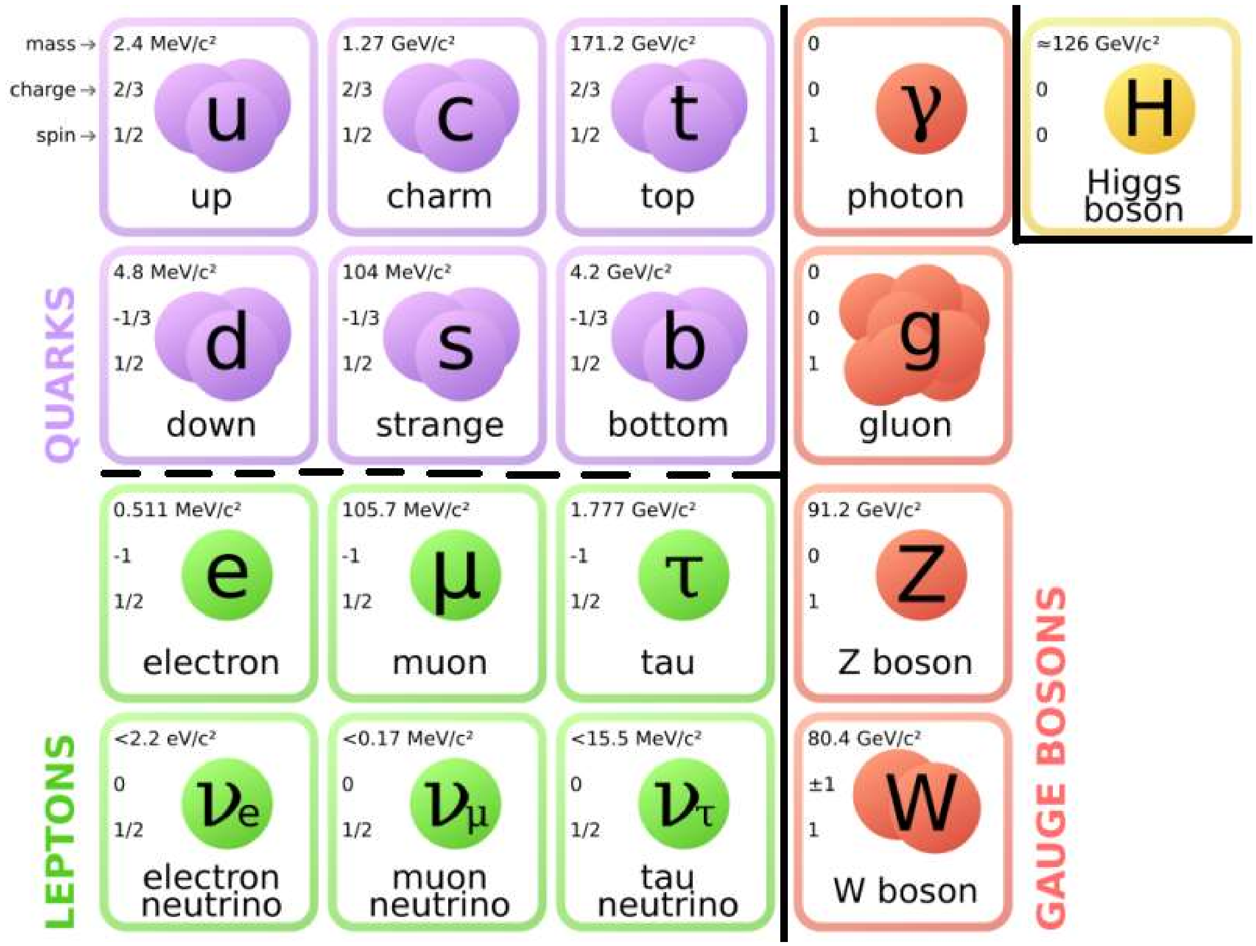

Figure 1.1: *The Standard Model of Particle Physics.*

Figure 1.1 shows one representation of the Standard Model. It is composed of the fundamental fermions, the force carriers, and the newly discovered Higgs. Elementary particles can be classified broadly by the magnitude of their spin and the value of their electric charges. Spin refers to the angular momentum of the particles and is generally given by the spin quantum number, which is obtained from dividing the spin angular momentum by the Planck constant ħ to reduce the spin to a simple whole- or half-integer value. In other words, the spin is a measurable physical attribute of each particle which can be represented as ½ or 1. Fermions are spin-½ particles, either leptons or quarks. Integer spin particles are called bosons, which include the force particles (photon, gluon, W and Z bosons) and the scalar boson, the Higgs. The elementary force particles, or gauge bosons, are force mediators that govern the fundamental electromagnetic, strong nuclear, and weak nuclear force interactions. The Higgs boson couples to elementary particles, giving all of them mass, and has spin 0. As for charges, quarks are distinguished from leptons as the only elementary particles that have fractional electric charges (either –1/3 or +2/3), as opposed to leptons which have unit charges.

The Standard Model of Particle Physics has been studied for over 50 years by a large number of increasingly complex experiments. It has been shown to be consistent with all experimental tests done to date. These experiments are the scientific community's way of exploring the fundamental workings of the universe and are the culmination of years of effort by many dedicated particle physicists, engineers, and technicians in the design and construction of accelerators and detectors as well as the analysis of the massive amounts of data produced by them.

1.2 CP-Symmetry and Violation

Although the Standard Model has been well verified, there are still mysteries that remain unsolved. Once such mystery is why the evolved universe is matter-dominated as opposed to being a mixture of matter and antimatter, which would be unstable. One plausible explanation proposed by Andrei Sakharov in 1967 is CP-violation, the violation of "Charge Parity-symmetry" [8]. In this case, symmetry means the invariance of a system under some operation or juxtaposition. CP-symmetry is a combination of two assumed fundamental symmetries of nature, charge conjugation and parity.

Charge-conjugation (C) symmetry assumes that a system of particles will exhibit the same physics as one composed of their antiparticles. An electron colliding with a positron would mutually annihilate each other and produce two gamma ray photons emitted in opposite directions based on the laws of conservation of energy and momentum. C-symmetry assumes that exchanging each particle for its antiparticle, seemingly switching each's charge, would yield identical results. In other words the laws of physics remain invariant under such a symmetry transformation. So a positron colliding with an electron would annihilate and similarly produce two gamma ray photons in the same final state as before. Parity (P) symmetry assumes that physics is invariant under a coordinate system transform of X to –X (or of any other single coordinate axis). This transform is similar to viewing a constructed system as in a mirror. An interaction in a given system is assumed under P-symmetry to be equivalent with the interactions in the mirrored-coordinate system. Together these assumed natural symmetries are coupled in order to form Charge Parity symmetry, the necessity for such a supposition being caused by the experimental violation of Parity symmetry [8]. At one point, it was believed that it shouldn't matter whether a system is measured relative to one coordinate system versus its mirror image. But this was found to be violated, so in an effort to establish a symmetry that was not violated we conjectured that perhaps CP-symmetry is universal. Simply put, CP-symmetry is an assumption that the laws of physics are invariant if a particle can be transformed into its antiparticle while at the same time it undergoes a mirror image transformation.

Strangely enough, if this symmetry was intact after the Big Bang then matter and antimatter would have been produced in equal quantities and would have eventually combined to annihilate each other, in the end leaving nothing but a universe full of matterless radiation. However, with CP-symmetry violated, there is the possibility of a matter-dominated universe that can survive to the present day. Since the latter is the actual case, particle physicists are working to study the effects and consequences of CP-violation to better understand how violation occurs.

When CP-symmetry is violated, there are identifiable phenomena that can be measured, which will be explained later on. The main issues for studying the phenomena lie in producing a system where they will manifest, and then measuring their nature precisely and accurately. Before the development of particle detectors, the conditions for CP-violation to occur by a measurable degree could only be found over 13 billion years ago during the Big Bang, so our only hope was in the artificial recreation of a system possessing energy values exceeding those found at the core of the sun. The other side of the problem would be in measuring the energy, mass, position, velocity, and charge of subnuclear particles, and in measuring enough of them to yield purposeful data. But it gets even more complicated when considering both these conditions must be met at the same time. Therefore, you need equipment sensitive enough to register a passing electron to be operating in front of an ideally formed hurricane of post-Creation chaos. You can then study the behavior of the particles in question, extract the measurable quantities, and compare results with the related theory to assure viability of its explanations.

Enter LHC, stage left.

1.3 The Large Hadron Collider

The Large Hadron Collider (LHC) is a particle accelerator, 27 kilometers in circumference and located approximately 100 meters underground, beneath the Franco-Swiss border near Geneva, Switzerland [3]. It consists of a circular beamline surrounded by superconducting magnets which contain and direct two beams of protons travelling in opposite directions around the ring at near the speed of light and then force the bunches of protons to collide, thus emitting new particles for study. It was built by the European Organization for Nuclear Research (CERN), starting in 1998 then taking ten years to complete, and its first successful circulation with recorded proton-proton collisions was on November 20, 2009 [3]. There are four main experiments being conducted at different interaction points along its length: ATLAS, ALICE, CMS, and LHCb (the “b” is for beauty, as in the beauty quark).

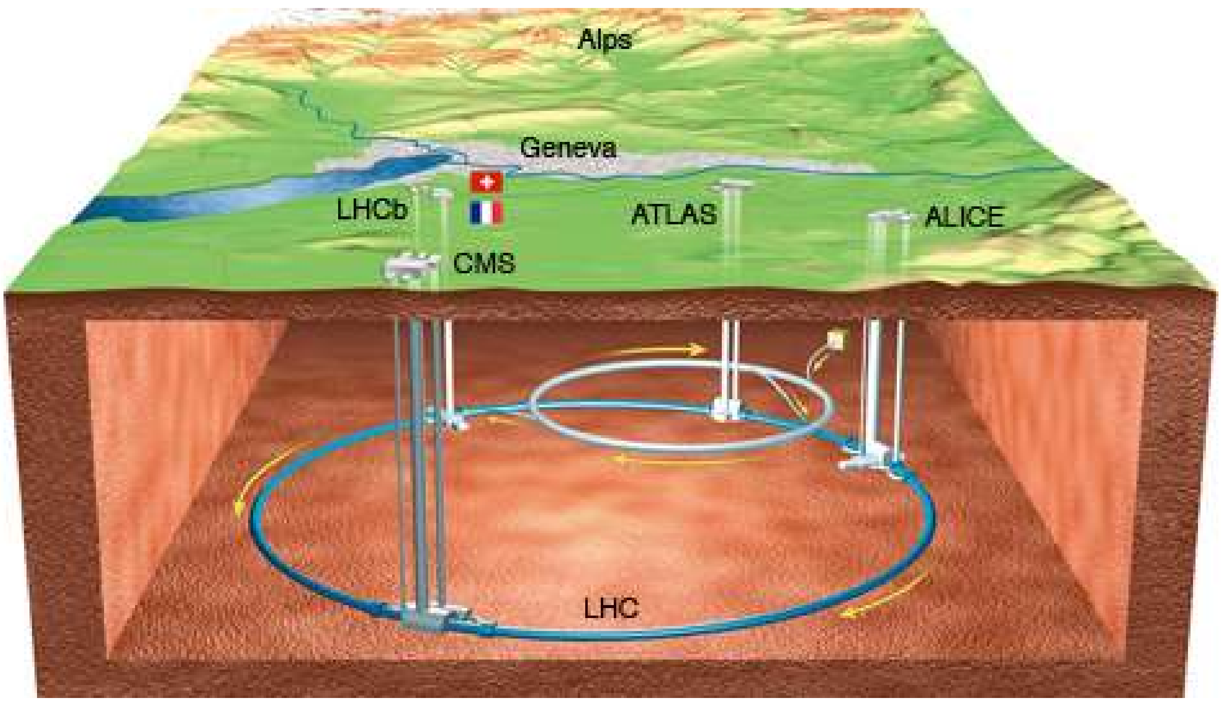

Figure 1.2: *LHC underground and LHCb.*

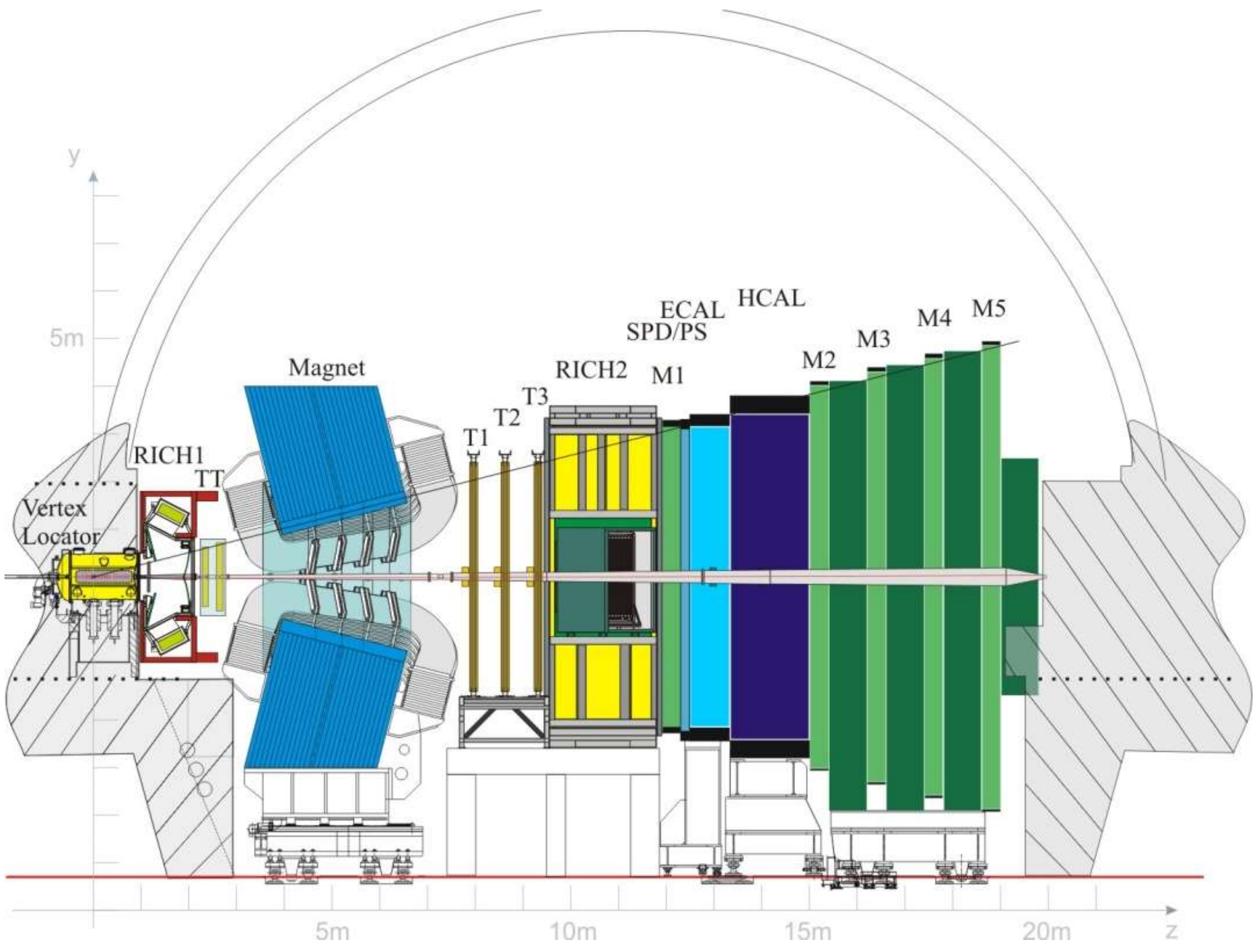

Figure 1.3: *LHCb sub-detectors [4].*

1.4 The LHCb Experiment

LHCb is a dedicated experiment for studying the physics of b quarks, including CP-violation and rare decays, New Physics, and other important phenomena.

When the bunches of protons collide with each other at the interaction point we are able to detect the generated subnuclear particles and their analogs, called hadrons. Hadrons are any particle composed of quarks, either a quark paired with an antiquark for a meson or three quarks together for a baryon. The three pairs of quarks displayed in Figure 1.1 in order of increasing mass are: up and down, strange and charm, and bottom and top. Bottom (b) quarks are relatively long-lived and more easily identifiable in experiments, and being a third generation quark means they are very important in the observation of CP-violation. CP-violation can be observed in the comparative amount of measured products from the decay of b quarks and anti-b quarks produced from high-energy collisions in LHCb. CP-violation is introduced into the Standard Model of Particle Physics as a complex phase shift in the wavefunctions of particles, meaning that b quarks can spontaneously transform to anti-b quarks and back again with some probability. Since we can experimentally produce b quarks in expected amounts, the rate of decay of a b-hadron can be compared to the corresponding decay rate of an anti-b hadron into the charge conjugate. Their final states will be compared and if they differ then it is an indication of CP-violation. A slight asymmetry in the number of matter particles over antimatter particles at the time of the Big Bang, perhaps generated by this mechanism, could possibly explain the seemingly matter-dominated universe.

The LHCb Experiment is mainly concerned with these heavier b particles. In the LHCb detector depicted in Figure 1.3, downstream from the interaction point, are several sub-systems for particle tracking, identification, and energy assessment.

The tracking system is composed of the VELO, T1-T3, and the TT. The VELO, or VErtex LOcator, is located closest to the interaction point and serves to track the origin points in space of the particles as they decay and change course. The silicon tracker and the outer tracker are farther down the beamline for precisely measuring charged particle tracks after passing through the magnet. The TT is located before the magnet and along with the T stations provide tracking information so as to determine particle momentum and charge. The silicon tracker and the TT are silicon-strip detectors, meaning they measure the electric charge collected on strips embedded in silicon from electrons kicked out of their atomic shells by a charged particle passing through the silicon. The outer trackers sit farther from the beamline and are composed of thousands of 5mm diameter straw-tube drift chambers filled with a gas that will ionize from passing particles and thus generate an electric signal.

The particle identification system includes the two Ring Imaging Cherenkov (RICH) detectors and the muon detector. When a charged particle passes through a dense gas faster than light would in that medium, it emits a cone of light similar to a sonic boom produced when a jet travels faster than sound would in air. The RICH is composed of a gas volume and photon sensors for measuring the light-boom cone's characteristics which is used to determine the particle type. The muon system consists of alternating gas chambers and absorber material, and detects muons which are the only particles which would pass through the thick absorber material.

The energy of a particle is measured by the calorimeters which sample the particles' energy as they pass through the subdetector and use the information to extrapolate the total energy that each particle had. There is the electromagnetic calorimeter to measure lighter particles such as electrons and photons, and the hadron calorimeter to measure the heavier particles such as protons and neutrons.

1.5 LHCb Upgrade

Data-taking is currently ongoing, but more data is needed since CP-violation occurs very rarely; so an upgrade to make the experiment faster and more sensitive is being planned for 2019 installation [5]. Approximately one in every 1000 interactions will be b-particle emitting and only a small subset of the subsequent decays will exhibit CP-violation. The rate of violation coupled with the desire for many data points means that in order to observe and study a satisfying amount of data on CP-violation we need at least 10^{12} interactions. The TT, a tracking detector, is one of the sub-detectors that will be replaced during the upgrade. The replacing subdetector is called the Upstream Tracker, or UT Tracker. It is this particular sub-detector upgrade program we at Syracuse University's High Energy Physics group are involved in. SU HEP is the lead research group and tasked with getting more efficient tracking, faster electronics readout, and improved solid angle acceptance.

Chapter 2:
UT Tracker

In this chapter, we discuss the UT Tracker's design and function. In particular we focus on the UT stave, the thermomechanical support structure we are trying to optimize with respect to mechanical stability and efficient cooling for its mounted electronics.

2.1 The UT Tracker

The UT Tracker, whose location within the LHCb is depicted in Figure 2.1, is meant to measure the paths, or "tracks," of charged particles as they pass through four planes of sensors oriented perpendicularly to the beam line. The UT is comprised of silicon sensors as the acting detector medium, custom front-end readout electronics, and novel thermomechanical support structures.

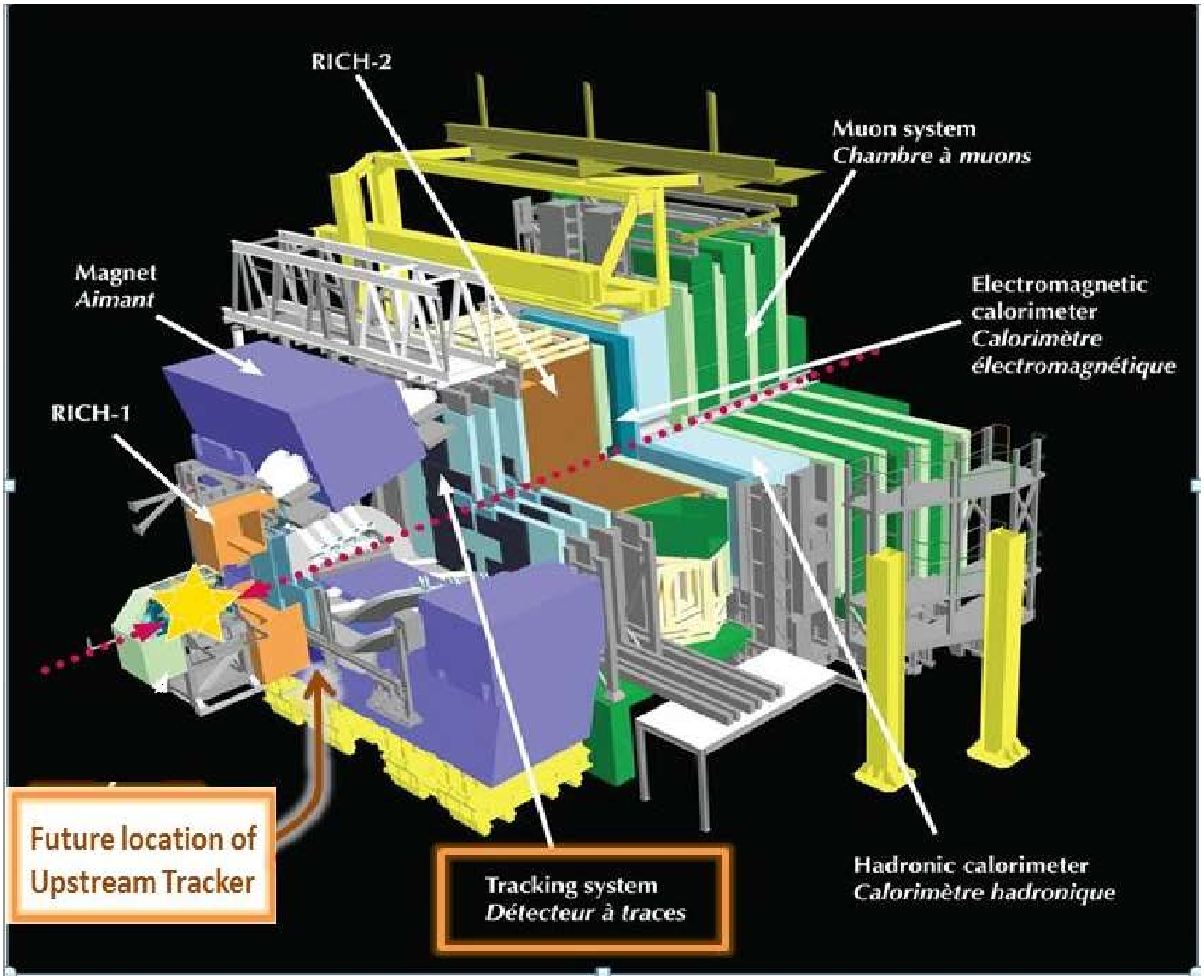

Figure 2.1: *LHCb upgraded detector showing future location of Upstream Tracker [5].*

The UT will be made up of four separate planes of silicon strip sensors facing the event vertex, the location where the two proton beams will cross. The first two sensor planes will have 16 staves and the next two planes farther down the beamline will have 18 staves [7]. Each stave is a tall, thin, stiff, and lightweight structure made to support 14 to 16 sensor modules. The sensors are vertically staggered alternatively on the front and back of the staves and the staves in turn are horizontally staggered on each plane to provide full sensor coverage, as viewable in Figure 2.2a with the alternating sensors and exposed orange flex cable where a sensor is on the rear of the stave. Figure 2.2b depicts how the planes will be oriented with respect to the beam line; all planes are perfectly perpendicular while the second and third planes have a stereo angle of ±5° [7]. This slanting serves to assist particle tracking by allowing a more accurate position measurement for a particle's track, similar to how the staggering of the sensors and the staves assures full coverage.

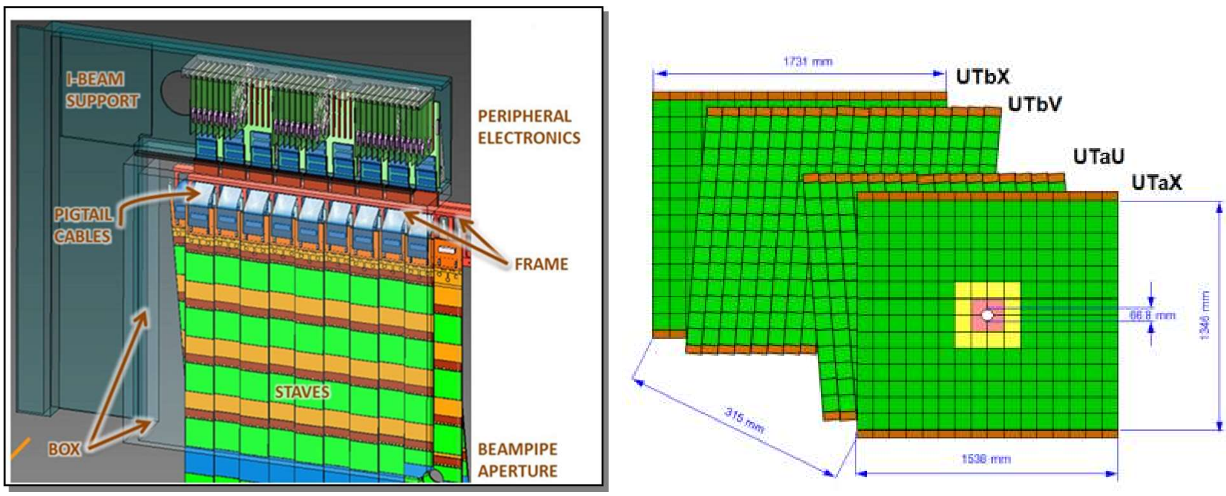

Figure 2.2: *Basic structure of the Upstream Tracker;* ***a)*** *sensor planes, wiring, and support structures [5];* ***b)*** *simplified diagram showing slant orientation of planes U and V [7].*

If none of the planes were slanted then the vertical strip sensors would be hard-pressed to provide vertical accuracy, which is not trivial. With one sensor plane angled by +5° and another by -5°, the vertical strips orient to form a crosshatched pattern, as seen in Figure 2.3. The crosshatched wire pattern provides more information regarding the vertical coordinate of the particle's measured track, which is important in order for the pattern recognition to distinguish multiple tracks in close proximity. Precise measurements in this detector are key due to the minute scale of the particles measured and because every interaction in LHCb produces around 100 particles at once. Therefore, the sensors' strips must be only 200μm apart to properly differentiate between two particle tracks [4].

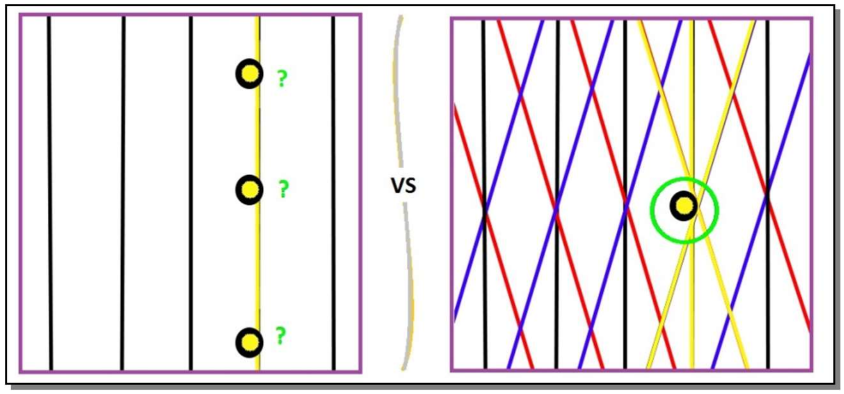

Figure 2.3: *Diagram illustrating improved vertical accuracy of approximated particle track in silicon strip detector via stereo angles applied to two sensor planes.*

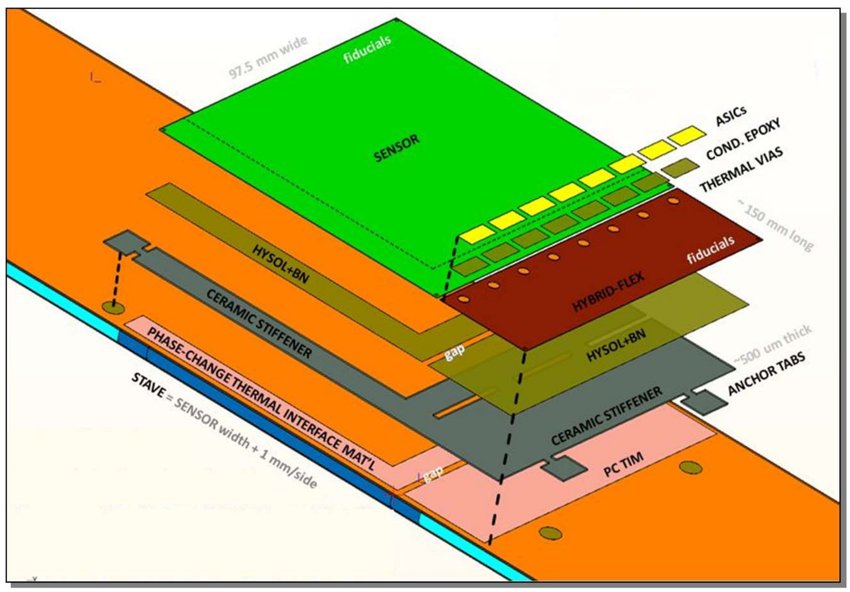

Figure 2.4: *UT Module showing sensor (green), ASICs (yellow), and hybrid stiffener (grey) [5].*

Each sensor module is designed as a multilayer structure, as can be seen in Figure 2.4. The silicon strip sensor is 250µm thick and 97.5x97.5mm^2 with ~190µm or ~95µm pitch strips [7]. When a charged particle goes through the sensor's silicon medium, it excites nearby electrons as it passes which are drawn by an applied electric potential difference of a few hundred volts to the electrodes. The electron's signal is amplified and detected, and the original particle's path is reconstructed from the data. The electrical impulses generated in the silicon and collected on the strip channels are sent to the ASICs via delicate wirebonds. The ASICs are Application Specific Integrated Circuits, high-level custom-made integrated circuit chips. They amplify and digitize signals, and drive the data at 320 MBits/sec down the flex cable covering the surface of the stave, and out to the later-stage electronics [4]. Both the sensors and the ASICs are mounted on a hybrid ceramic stiffener, and as a module unit it is mounted on a stave.

2.2 The Integrated Stave

The main unit for the UT Tracker is the integrated stave. The staves are designed to provide mechanical support for the sensors and allow thermal management for the heat loads. They require a construction tolerance of ~0.2mm, with a measured position accurate to 10μm, relative masslessness, and the ability to stiffly, stably hold approximately 800g each [7]. The staves need to have low mass because of our interest in having a large radiation length so as to keep the subdetectors from interfering with the particles they're meant to detect. Radiation length is a physical characteristic of materials that describes how susceptible an incident particle is to scattering, with a shorter length equating to more probable scattering. It is important since scattering causes the data points for one particle's track to not align properly and thus be lost.

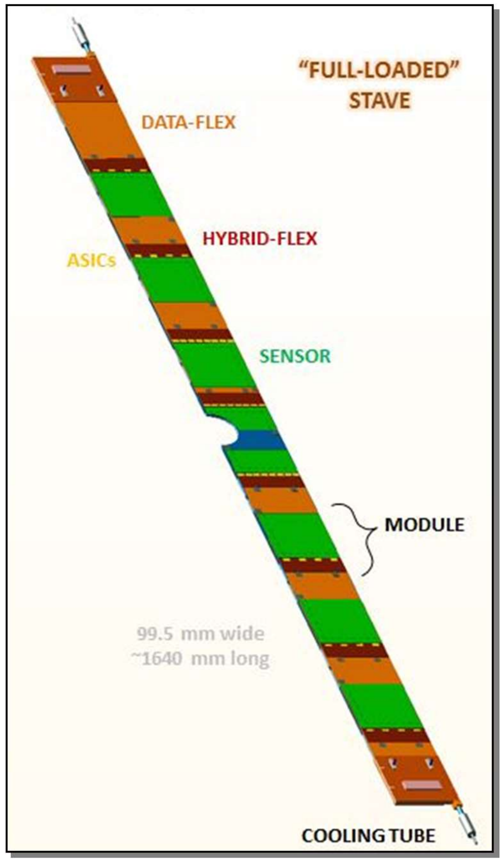

Figure 2.5: *Integrated stave overview [5].*

The staves are constructed from two stiff carbon fiber sheets (made of unidirectional carbon fiber strands epoxied together) which are sandwiching a light-mass carbon foam material (made of epoxied and aerated carbon, providing a relatively incompressible support and excellent thermal conductivity). Integrated within the sandwich is a titanium tube that is part of a cooling system.

The sensors must be kept at an optimal temperature of -5ºC so as to avoid increasing both power consumption that would prevent long-term stable detector operation, and the standing reverse bias current that would introduce much-unwanted noise to filter out of the detector data. The standing reverse bias current is the current produced when applying a reverse bias voltage over the silicon sensor, which is a diode. The heat loads are the ASICs and the silicon sensors.

The ASICs heat up due to Joule/resistive heating, the process of electric current passing through a conductor releasing heat. The silicon sensors would heat up due to “thermal runaway,” a positive feedback loop which could occur wherein the sensors suffer radiation damage during operation which increases the bias current which increases the sensor’s Joule heating which decreases effective resistance which in turn leads back to increasing the bias current [7]. As previously mentioned, this would cause too much noise, but it would also end up destroying the detector and must be prevented; therefore cooling the sensors must be a priority.

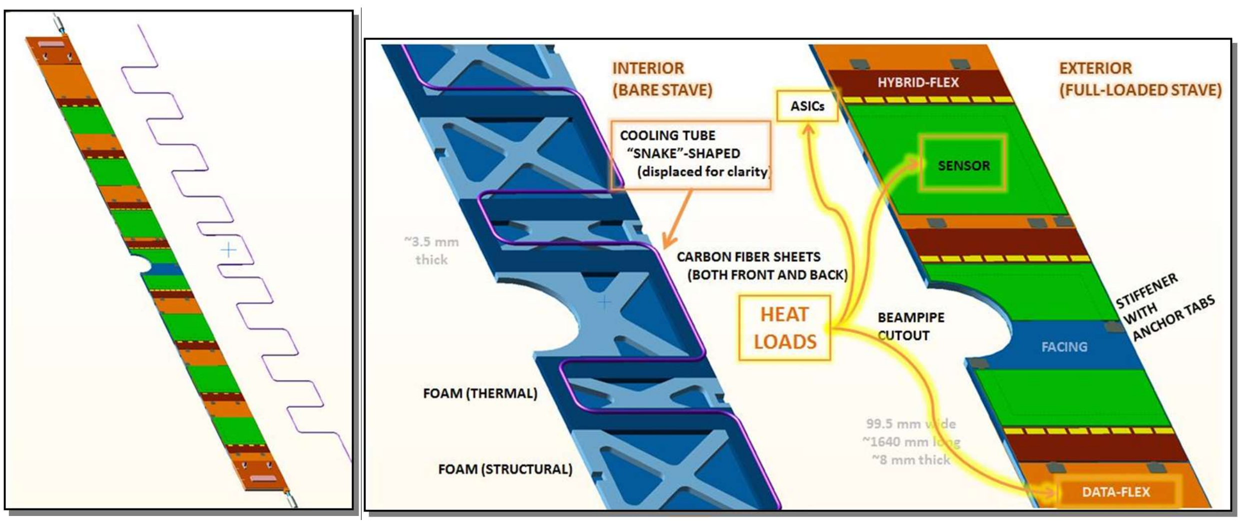

Figure 2.6: *Structure of Individual Stave Internally [5].*

Thermal management is handled by a coolant tube snaked through the entire stave directly under the heating components with liquid carbon dioxide running through it, evaporating and thus cooling the stave. The liquid CO_2 is pumped through by a sophisticated closed loop cooling system. This process is known as CO_2 bi-phase cooling, involving pumping liquid CO_2 into the coolant tubes which then boils, and the latent heat of vaporization acts to absorb heat from the stave. A similar system was designed to cool the VELO subdetector, and that system was adapted for use in the UT [11]. The tube, viewable in Figure 2.6b, is made of thin titanium with a 2.2mm diameter and 0.125mm wall thickness [7]. It is bonded to the carbon foam with thermally conductive epoxy and so is in thermal contact with hybrid modules on both sides of the stave.

CO_2 bi-phase cooling is the preferred choice for many reasons. First, it has a high latent heat of vaporization and is relatively low mass. CO_2 also performs better with smaller diameter pipes than other coolants since it evaporates at much higher pressures while the vapor volume stays low while compressed, thus allowing better flow. CO_2 out performs other coolants in heat-transfer conductance by volume so smaller tubes with smaller radiation lengths are viable. It is additionally practical, as it is not flammable, nontoxic, low cost, and nonharmful to electronics.

There have been no significant tests of a system for CO_2 cooling like ours with a vertical system such as the stave. We want to compare the change in pressure, the flow rate, the temperature difference along the stave, and the percentage of evaporation in the horizontal vs vertical CO_2 bi-phase cooling systems. The focus of this capstone was developed from the desire to evaluate what is the most efficient cooling process for these staves.

2.3 Early Stave R&D: Design Evaluation and Construction Techniques

The staves must have as little mass as possible while retaining structural rigidity and strength. In an effort to reduce the stave's mass, we investigated cutting out different patterns from the carbon fiber facings of the stave. Figure 2.7 shows a page from my workbook depicting sketches of different starter concepts. On the right is an image of a workbook page where I calculated the surface area that we would be removing to give us a rough percentage associated with each design. From these values and surface density measurements of the carbon fiber sheets, we estimated the reduction in mass.

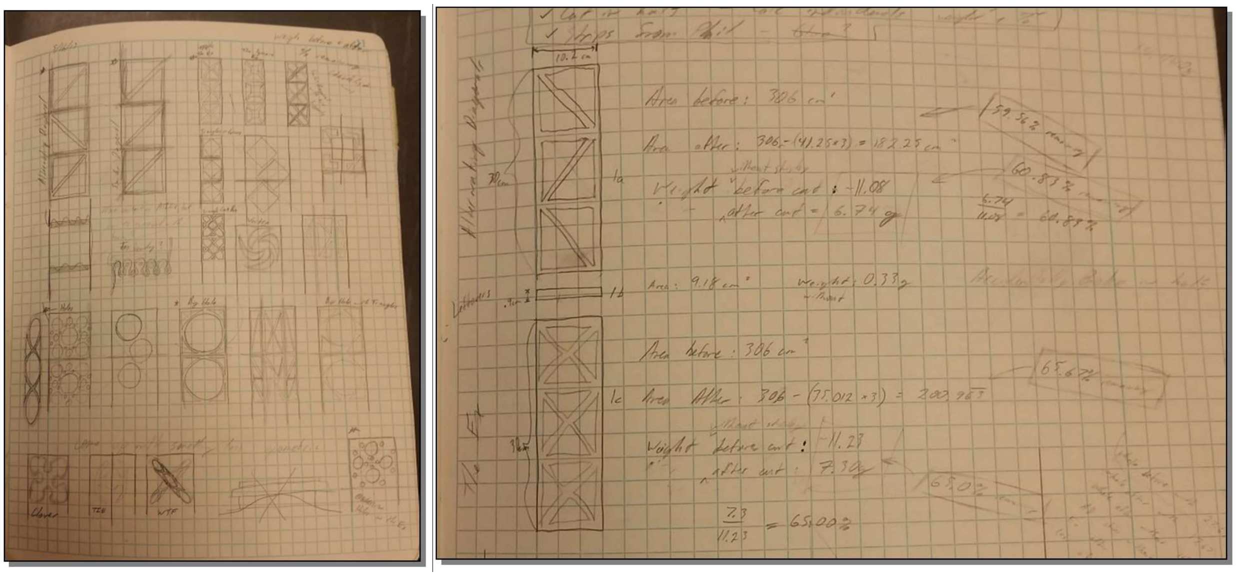

Figure 2.7: *Images of lab notebook;* **a)** *sketches for choosing facing cutout designs;* **b)** *area evaluation calculations.*

Once we had our favorite concepts for stave designs chosen, I produced several quarter-length staves (each of the three square sections is ~10cm^2, and each full-length stave is 120cm long) so that we could perform measurements to evaluate their stiffness. Several of these constructed quarters are depicted in Figure 2.8.

Figure 2.8: *Prototypes for mass and stiffness evaluation.*

The selection of design concepts to be constructed next was determined by either our personal judgement, or the performance of previously tested designs and how each compared to the expectations we'd had for it. As we had high hopes for a slim simple central X, the third stave (starting from the left) shown in Figure 2.8 was the first constructed. Not depicted was the "solid" stave which was made next and with no cutouts to give a "max stiffness" reference. The stave pictured second to left was meant to be our "minimum stiffness" reference, and was constructed third. After measuring these first three, we found that the simple X was less stiff than we would have hoped so we decided to try the hole-punched design next. The idea of the hole pattern of the left-most stave depicted was to preserve the central X sections while also retaining a "netting" between the arms of the X to help stiffen it. The fourth and fifth are orange due to a Kapton film epoxied to each outer side as a mockup of the Kapton Flex strip on the original full-length stave and are meant to test how much rigidity they provide to the structure. The sixth, rightmost stave is made only of the pink insulation foam we used for a sandwiching material, in place of the expensive carbon foam, between the carbon fiber facings to provide thickness to the stave and thus increase torsional strength. There were other designs made that have been appropriated for various uses and could not be pictured above, including a stave with a wider design for the arms of the X and another with a single large hole in each of its three sections. Other staves were constructed with the foam ribbing material forming the central X shape, including one ¼ stave with a solid facing and one with a similar facing cut out pattern as the third stave in Figure 2.8.

The total mass of each final sample and its initial components is important to record in order to be sure the samples' differences lie in their cutout design more than in amounts of epoxy used. So we first measured the mass of each of the components (two carbon fiber facings measured before cuts were made, and after cuts were made, along with the pink foam measured after being cut from blocks into strips) and then glued one carbon fiber facing to the pink foam strips. After the epoxy dried, we would record the sample's mass and calculate how much epoxy was used. Then the same for epoxying the other carbon fiber face on. Once the gluing was complete we knew how much mass each sample's components weighed, so we could compare them. After construction, I would evaluate the overall stiffness of each.

The Dylatron (named after its constructor, a fellow undergraduate named Dylan Hsu) was used to test how stiff each sample was, as depicted in Figure 2.9a. The samples were supported simply on each end, and a plunger attached to a spring force gauge was pressed onto a particular point on the stave. This caused it to deform and a manual micrometer tool (accurate to +/-0.0001 inches) was used to measure the displacement from below. Each stave had four points of interest, located at the center of each side of the central square region. Figure 2.9b depicts one form of data analysis on the results of these tests. Each line on the graph is a set of data for a different stave, plotting Force vs. Displacement. From these graphs we evaluated whether removing sections of the facings was worth the reduction in mass. Our conclusion from these tests was that cutting patterns would reduce the structural integrity by more than what the mass reduction would be worth, but that the foam ribs under the X were worth the added mass. Therefore it was decided that the final prototype would be lacking any cutout pattern in the facings but include the X pattern for the internal support foam.

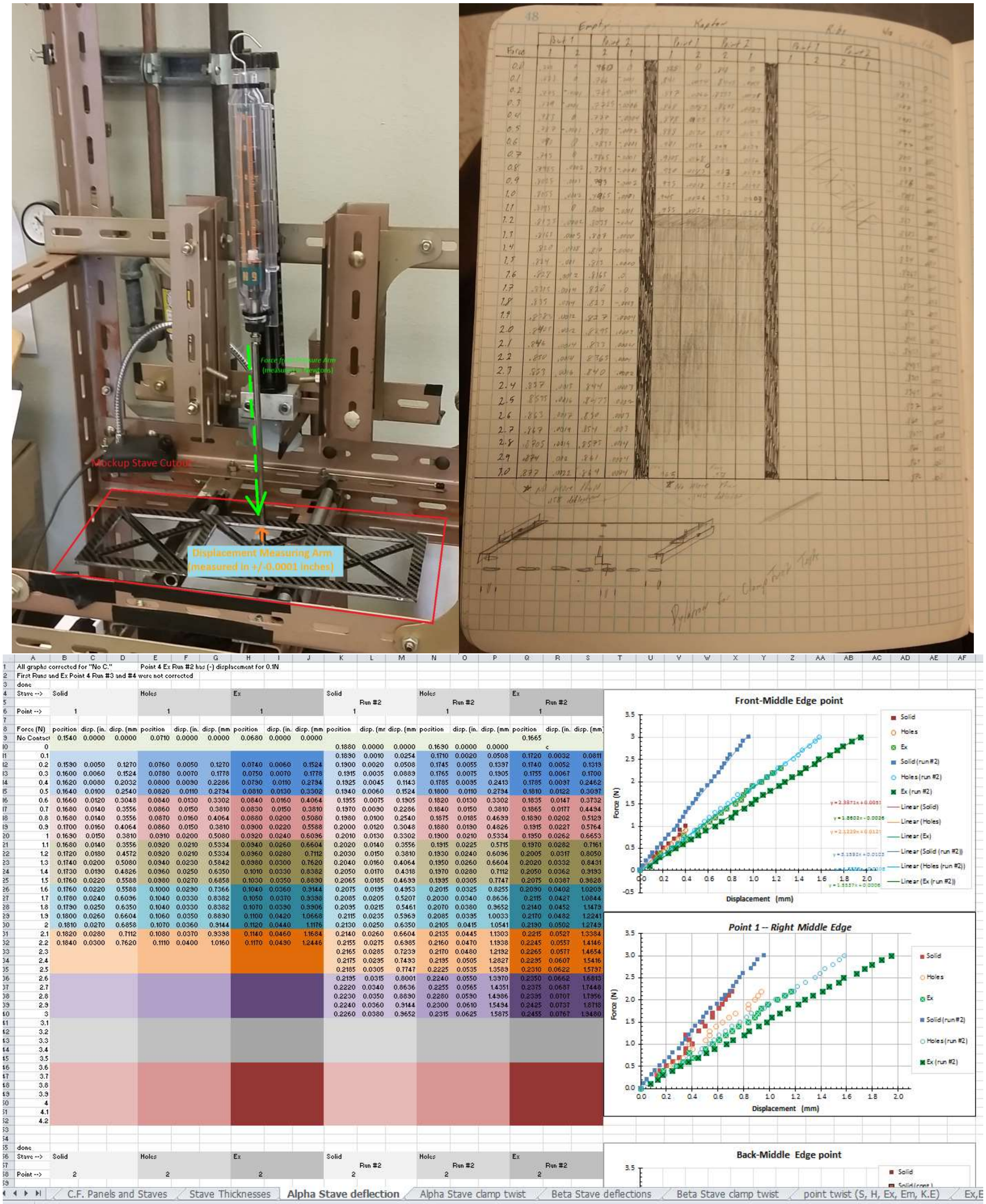

Figure 2.9: *Stiffness evaluation process;* **a)** *single stave on Dylatron;* **b)** *capture of recorded data in lab notebook;* **c)** *data comparison in Excel.*

2.4 Early Stave R&D: Cooling Tube Pressure Testing

Figure 2.10 depicts the containment (left) and the control (right) setup for our tests concerning pressure within the metal cooling tubes. CO_2 will be held at around 1500 psi and fittings would be necessary for the tubing of the stave, so we performed tests to evaluate which bonding agent would be best to use for joining fittings. Our options were Armstrong epoxy, Araldite epoxy, and a metal brazing technique. There is a ~20cm long section of titanium tubing, capped with an epoxy or brazing at one end and attached to the pressure system at the other.

As one part of the pressure tests, the tubes were brought up gradually over an hour to 2300 psi and left overnight with a camera taking snapshots of the pressure gauge for monitoring leakage rates. The next part involved temperature cycling them into and out of a -20ºC fridge every half hour for four times to simulate runs being cycled in LHCb, then again brought gradually to 2300 psi and left for a night. The third and final part of testing involved rapidly achieving 2300psi over 5 minutes then leaking the pressure down to 100 psi over another 5 minutes, and repeating this pressure cycling for five times. Our conclusion after these tests was that all epoxies behaved acceptably, but with further evaluations we settled on brazing out of concern for potential chemical reactions between the epoxies and the CO_2.

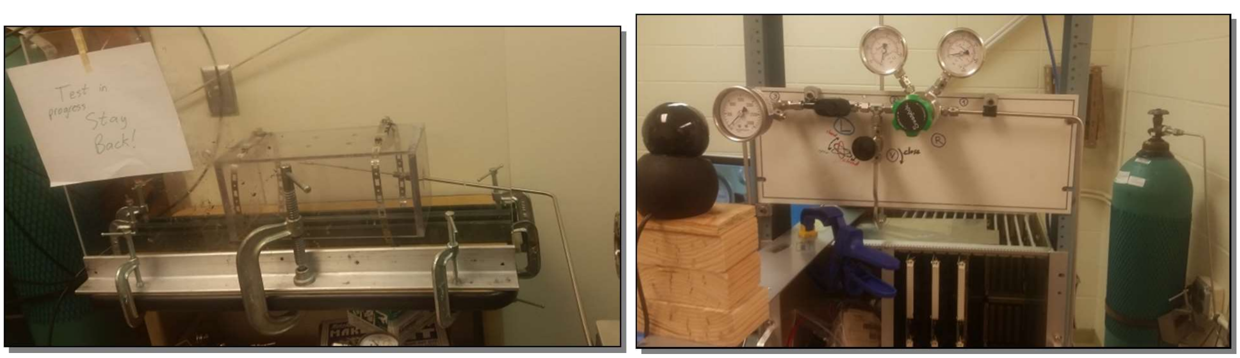

Figure 2.10: *Short Pressure Test evaluation process;* **a)** *blow-out containment area;* **b)** *pressure control and gauge readout.*

After evaluating the proper design of the stave carbon fiber sheets and what type of epoxy to seal fittings with, we were ready to gather material and construct mock staves to begin thermal evaluation. The first step in this process involved constructing a coolant delivery system and an insulating container for the stave to be tested in, settling on a coolant, and standardizing the testing procedures concerning RTD placement along with data acquisition and analysis. Later we would use that knowledge to design and construct a new insulating container for testing higher-quality mock staves with better accuracy, better precision, and new techniques.

Chapter 3:
Stave Thermal Isolation Testing

In this chapter, we solidly introduce the main focus of this capstone: the TIEC, the Thermal Isolation Experiment Case, affectionately referred to as the BoB for "Box of Boxes." We first discuss the previous work done on the thermal isolation testing and our preferred areas for improvement, which became the rationale behind my project, then frame what we aimed to accomplish when we began.

3.1 Rationale Behind Constructing a Thermal Isolation Case

In the UT, there is power dissipation in the ASICs and sensors. The sensors should operate at -5°C, but will heat up primarily due to the close-by readout electronics. To control the temperature of the sensors, a powerful cooling system is integrated into the stave structure that uses a process of evaporating CO_2. A proper cooling system must be tested and measured in order to refine the design and maximize its efficiency, so our research group set about doing just that. This process of refining the system requires a setup for testing the stave that fulfills these requirements: (1) thermally isolates the stave from the environment, (2) allows access to power (heat) the mock-up/prototype stave properly, (3) allows for measuring mechanical deformations and temperature accurately and precisely at many points, and (4) ideally allows for infrared imaging.

3.2 Pink Panther Box

The refining process began with a horizontal experiment case made of Pink Panther Styrofoam insulating foam with the initial intent of establishing baseline thermomechanical behavior of a prototype stave. To accomplish this, we wanted to figure out the following: how and where to place the RTDs (Resistance Temperature Detectors) on the stave, how to receive a digital readout of the data from the electronics, how to write a program for evaluating the data (calculations, conversions, plotting, saving, etc.), which coolant to use (water and glycol mix, CO_2, liquid nitrogen), how to pump/control the coolant flow and how to route it to the stave. All of this should be decided upon before we acquire a suitable testing arrangement that would allow for these newly standardized techniques to be making accurate measurements.

Figure 3.1: *First attempt at thermomechanical evaluation, the Pink Panther Test Box (horizontal box on right), and flow control apparatus for liquid* CO_2 *(on left).*

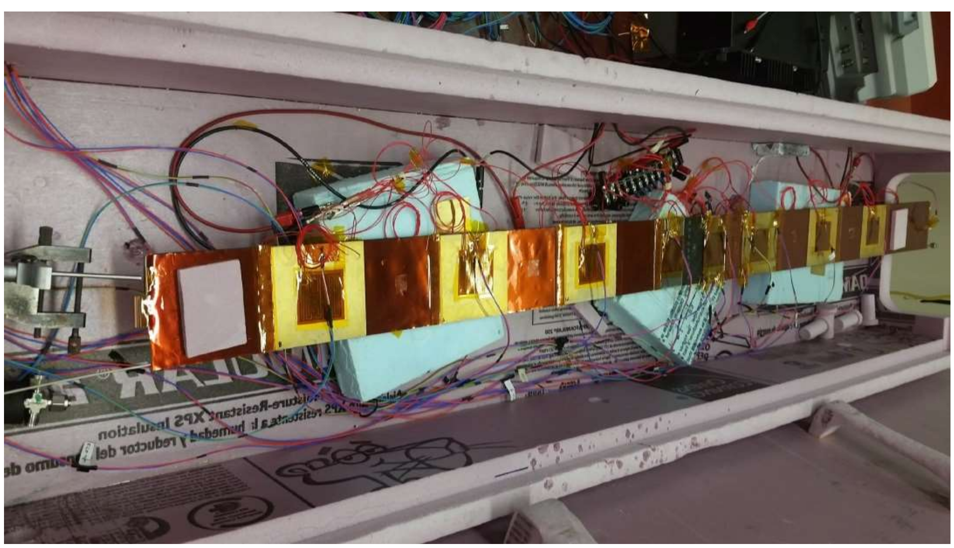

Figure 3.2: *Pink Panther thermomechanical evaluation process.*

Figure 3.2 depicts the inside of the Pink Panther test box, the ancestor of the more structurally sound polycarbonate and aluminum Thermal Isolation Evaluation Case. Here we can see the wiring for the RTDs and heaters on a full length mockup stave complete with its internal cooling tube. Its early stages of testing involved deciding between which coolant to use, as we hadn't converged on using a CO_2 bi-phase system. The first coolant was a water and glycol solution, next came liquid nitrogen evaporative cooling, and third was CO_2 bi-phase evaporative cooling. After completing evaluations of their comparative performances, we chose CO_2.

Unfortunately, after some time in operation the Pink Panther presented several flaws that we needed to remedy with the next design for a test box. One problem is the Pink Panther test box must be operated with the lid on and thus does not allow IR imaging without needing to expose the test to humid external air, which will cause undesirable icing over the chilled sensors. Another problem is that the pink panther material is not sturdy enough to be stood vertically and maintain steadiness, as is the staves' proper orientation during operation and therefore the most desirable orientation during testing. A third problem is that it isn't airtight, so the cool air within surrounding the stave is always being circulated with warmer air and making it difficult for the extremities of the stave to reach the desired test temperature. And fourth, the material did not allow for any mounting of displacement measuring devices since it is so soft. All these problems presented serious concerns when we considered what the next step would be in the project. Rather than try to improve on the Pink Panther box and its design to prepare it for more quality tests, we decided to build a new thermal isolation case from scratch.

3.3 The Purpose of the New Experiment Case

While working as part of the High Energy Physics group at Syracuse University, under Professor Raymond Mountain, I've worked on a setup to make measurements for testing the performance of various stave designs vertically. The future goal is to evaluate each prototype design to determine the optimal design and materials, and ultimately to test all production staves constructed for use in the UT Tracker. I've used a Computer Aided Design (CAD) program to design a thermally insulated eight foot tall, two foot wide, and one foot deep box made from polycarbonate panels and aluminum blocks, rods, and panels. I would later be using this Thermal Isolation Experiment Case (TIEC) to test the cooling capabilities of several layouts as mentioned above, including different routings of CO_2 cooling tubes. We will be testing the staves for their thermal and thermo-mechanical performance, performing optimization studies, and converging on a tubing layout that meets our mechanical requirements.

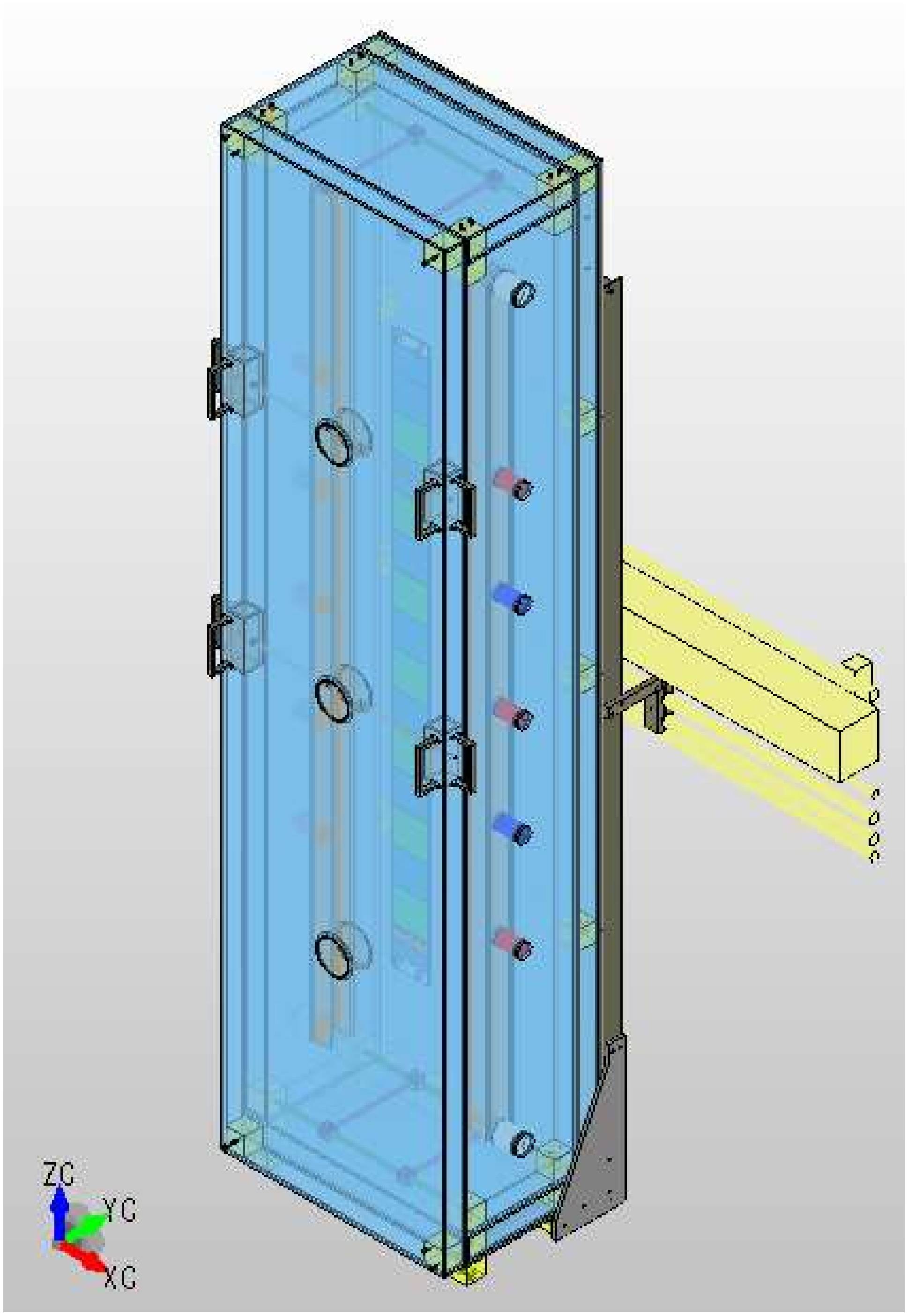

Figure 3.3: *The TIEC as of 2016 July 01, (complete design).*

Chapter 4:
Design of the Thermal Isolation Experiment Case (TIEC)

In this chapter, we discuss all the planning that went into producing the TIEC. We outline our design's requirements and concepts, briefly walk through the digital construction, and explain some of the physical motivations for our design choices.

4.1 Early Stages of Design: Concept

The requirements we'd initially set out to accommodate include: large enough to fit up to three staves, vertical in orientation, internal structure for support (hanging of a stave vertically), thermally isolating (has 2" still air insulation "sectioned" off as sides of the overall case), one removable side to act as a door/lid, a stiff aluminum skeleton for fixing together the case and giving rigidity, a method of internal access for wiring and coolant tubing, viewing ports for infrared imaging of the stave, and translucent material to visually observe the apparatus for measuring stave displacement and to monitor the stave for icing. Our choices were limited to acrylic or polycarbonate, and as acrylic is brittle enough to snap during fabrication we elected for the tougher material.

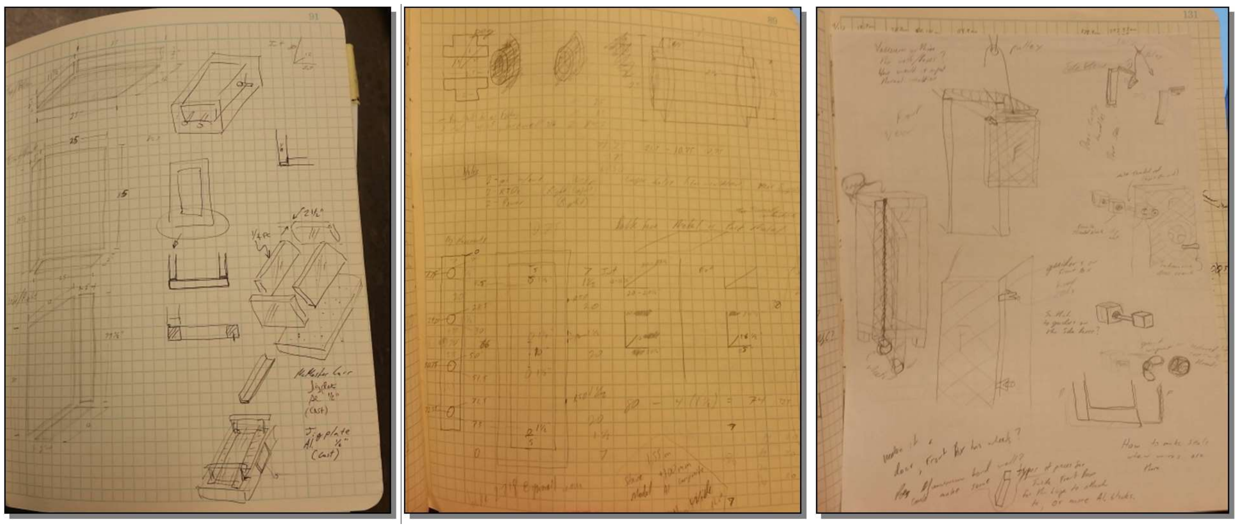

Figure 4.1: *First drafted designs for TIEC.*

After deciding that a polycarbonate box was what we wanted, I began designing. Figure 4.1 displays images of my workbook with sketches for the early concepts of our test box. The key idea for achieving insulation was to make six boxes, shown in 4.1a, that were all 2 inches thick internally, and use them as the sides of a larger case. The individual sides would be filled with still dry air to insulate the test contained within. Later on we considered using a vacuum setting for the insides of the walls to improve the insulation quality even further, but decided it would be better to stick with simple still air and label that idea as a potential future upgrade for the TIEC, affectionately referred to as the BoB for “Box of Boxes.” Figure 4.1b depicts early design concepts for the ports in the sides of the BoB that would allow access for the coolant tubes and the power and data wires to the mock heating pads and RTDs, and the last image shows concepts for how to convert the Front side case to function as a door.

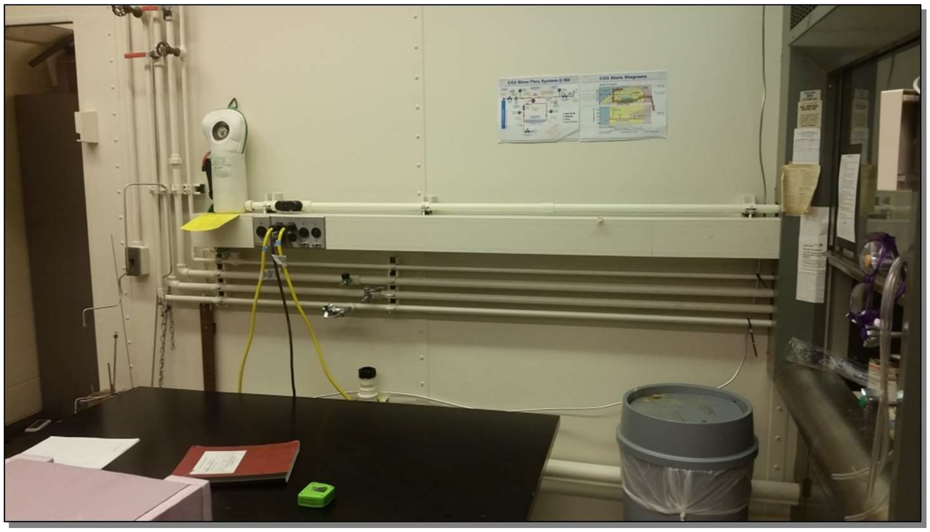

Figure 4.2: *One of the possible future locations of the TIEC.*

When considering suitable locations for the BoB to stand in our lab, we preferred the idea of setting it up next to our fume hood (on the right in Figure 4.2), and in front of some pipes as they would allow us to secure the BoB without necessitating the drilling of new holes into the wall since the pipes were already fixed securely to the wall. Later, after assembly, this space was no longer available and the BoB was positioned farther along the pipes, which turn at the room's corner to stretch along two walls of our lab. It is now set up in its own corner with space for the cooling system nearby.

4.2 Mid-Stage Design: CAD Model

The images in Figure 4.3 are depicting the progression of the BoB's digital design. Part A shows my first attempt at using the CAD program called KeyCreator, where I modeled the Pink Panther test box in an exploded view. The figure's next image shows the beginnings of the BoB's sides. At this point we had decided on the appropriate dimensions for accommodating up to three staves hung side-by-side vertically, and the general placement of the sides (the Left and

Right sides sit between the Top and Bottom, and all four of those sides sit between the Front and Back). The BoB as depicted in the third image of the figure is about half way through being designed. Now added are the seven ports on either side made from hollow polycarbonate cylinders to allow internal access by power and data cables along with the cooling tubes. There is also a stave included for scale reference and a rudimentary stave suspension rig in the top portion of the BoB. After deciding we would strengthen the polycarbonate structure with an aluminum frame, the CAD model resembled the final image in Figure 4.3. Seen now included in the design are the aluminum 2” cube triplets at each corner serving to fasten all six polycarbonate side cases together, the aluminum plates entirely covering both the rear and bottom faces which bolt to more aluminum cubes within the side cases, the aluminum L-beams running up the back edges, the large viewing ports in the front, the door structure including the handles and support cross-rods which both attach to the blocks at the rods’ ends, the modified suspension rig, the rear arm clamps seen attached to the modeled wall pipes, and 2” cubes on the underside to serve as feet.

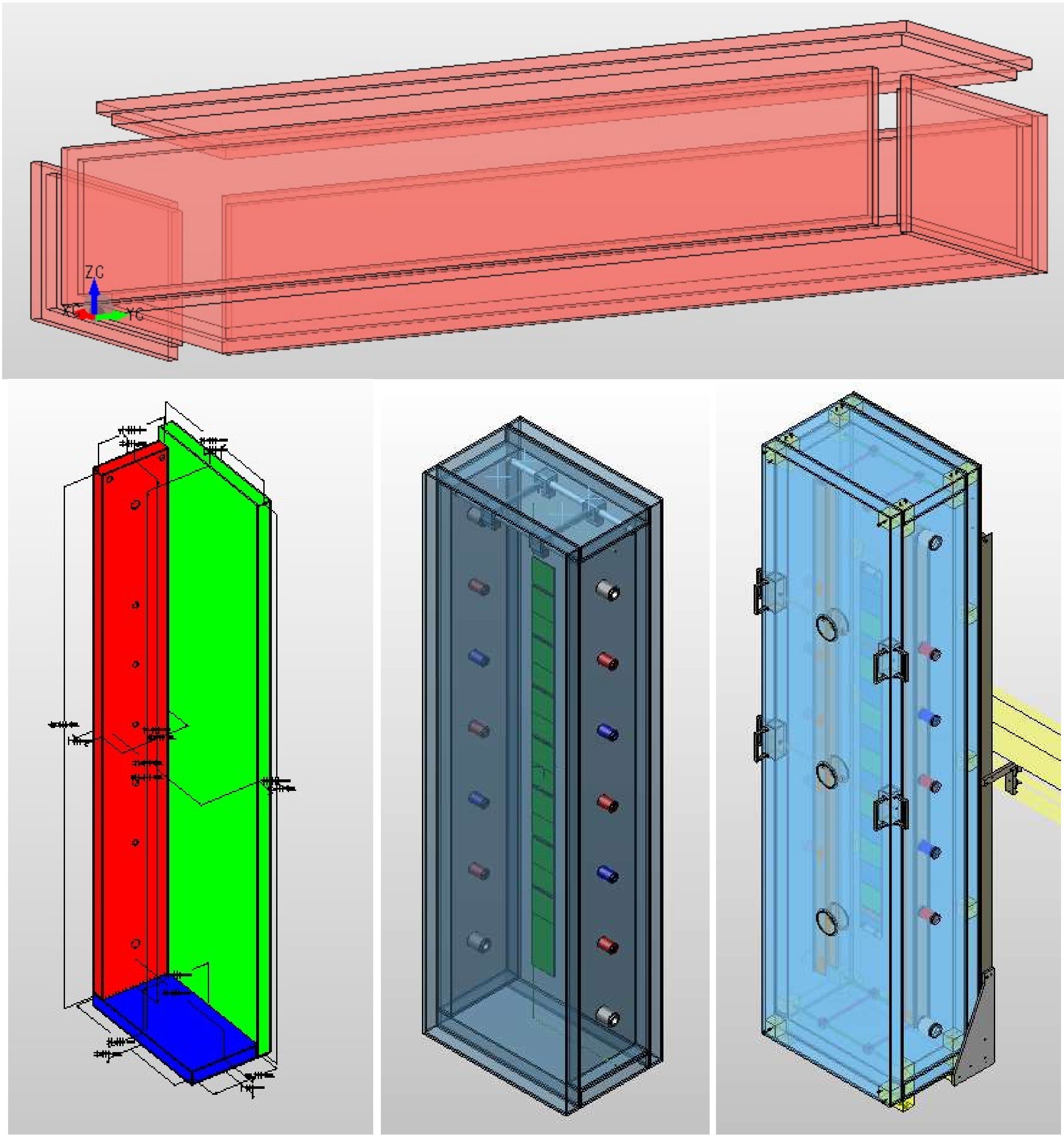

Figure 4.3: *Design evolution of the TIEC* **a)** *getting practice in KeyCreator with a first attempt at modeling the Pink Panther;* **b)** *starting to design the general form of the TIEC;* **c)** *partially complete TIEC on KeyCreator;* **d)** *completed and redesigned TIEC.*

4.3 Late Stage Design: Construction and Redesign

After completing a rough design draft that highlighted the more important features, I started construction. We decided to begin fabricating before finishing the design so that we could evaluate the BoB's properties as it was assembled. This would allow us to answer any questions we had about material performances and finalize any outstanding design decisions or come up with new solutions to meet our reimagined needs.

Figure 4.4: *Epoxy adhesion assessment;* **a)** *how the epoxy tests were prepared;* **b)** *tests of adherence of aluminum to polycarbonate: Hysol (top left two), Araldite (right-most two), and Armstrong (brown colored two).*

One question to be answered in designing the BoB was how to adhere everything together. For the polycarbonate-to-polycarbonate bonds we would use plastic weld to effectively fuse pieces together, but we had to use something else for the aluminum-to-polycarbonate bonds as we tested and confirmed that the plastic weld would not adhere properly with aluminum. So we chose three epoxies to compare: Hysol, Araldite, and Armstrong. We epoxied polycarbonate disks to aluminum blocks (with their surfaces prepped to resemble the surfaces of the BoB's blocks) and tore them apart by hand, judging how much strength was required to pull them apart. Although this was not a precise method, the results were straightforward to interpret. Our conclusion was that araldite was the epoxy that adhered most desirably.

Another question concerned the overall structural soundness and stability of the BoB. We were unsure about the structural strength of a case composed solely of polycarbonate, and so included aluminum cubes to fix things together, but the aluminum is much more massive than polycarbonate so will the aluminum structure be strong enough to hold both itself and the polycarbonate adequately?

These were questions only answerable after a certain degree of construction and evaluation, specifically after completely assembling the aluminum skeleton to be discussed in Chapter 5. During the time it took to fabricate all the pieces, make ready to assemble, then evaluate its performance, there were also several alterations made to the BoB's design including: the door, the bottom side back corner triangle brace, the rear bottom l-beam brace and then the reinforced l-beam brace, adding more feet for the rear edge, modifying the wall clamp arms, etc. These modifications were made to increase the structure's stability.

Chapter 5:
Construction of Thermal Isolation Experiment Case

In this chapter, we describe the TIEC construction processes and techniques. We touch on our initial provisions, depict the succession of components in their fabrication, discuss the alterations we made in our designs, and describe the sequence of final assembly.

5.1 Starter Materials and Techniques

The BoB began mostly as four 8ft x 4ft polycarbonate sheets and several 2” x 2” aluminum bars, along with a few aluminum rods, some polycarbonate tubes, and tons of screws. From these starter materials, we used a machine-guided vertical mill to cut out the sides of the BoB, a manual vertical milling station to shape and surface the corner cubes, lathed the support crossbeams and side ports and their plugs, and drilled out clearance holes or threaded screw holes.

5.2 Aluminum Construction and Dry Assembly

The first step was to construct the Aluminum 6061 alloy support skeleton, depicted in its entirety in Figure 5.1. We decided to construct it before fabricating the polycarbonate pieces because if the frame wasn’t strong enough and we needed to change our designs somewhat, then it would be easier to strengthen the support structure and not have to scrap the polycarbonate pieces thanks to their previous cuts no longer being on spec. So we would begin with forming all

24 nearly identical corner cubes, each being 2x2x2 in^3 accurate to within ±0.01in. This fabrication, like all done for this project, was done by me in the SU Physics Department Machine Shop.

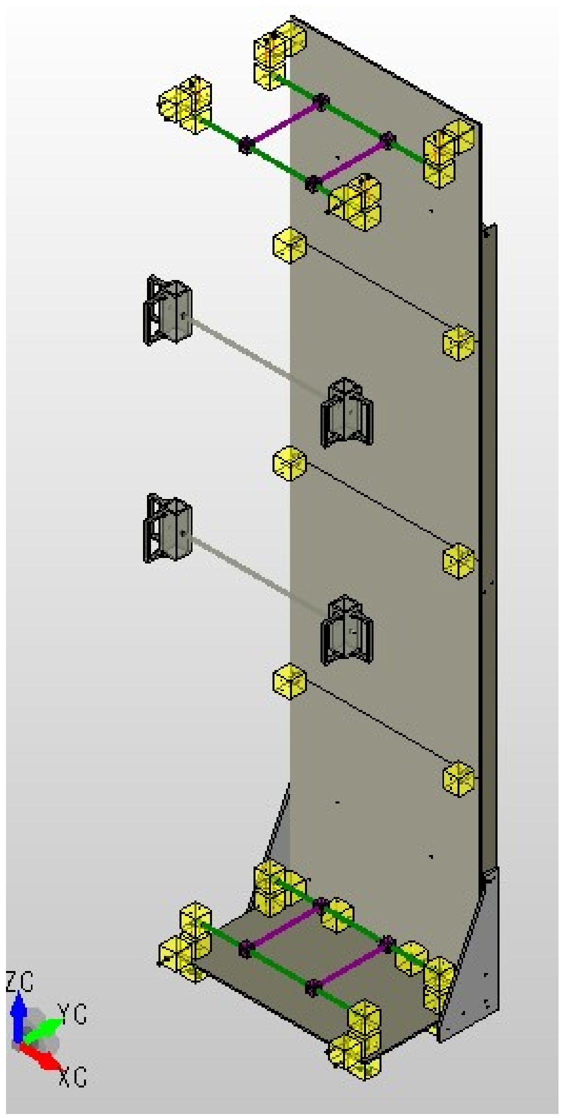

Figure 5.1: *CAD image of aluminum support frame. All the aluminum and only the aluminum. Cubes are shown in yellow.*

First the cubes had to be cut from a 2.025in square bar that was 4ft long. Figure 5.2a depicts the final cube from that bar being trimmed with the hydraulic bandsaw used to cut all the others. The bar is clamped in place, and a circular bandsaw moves on a long cutting arm which slowly lowers the saw blade into the material at an adjustable rate. It made very rough cuts so once the cubes were near their correct size we had to take them to a Bridgeport vertical milling station to shape them precisely. This process is very slow unfortunately, as the fly cutter can only mill off 0.020 inches every pass and it travels at a slow rate, so the rough bandsaw cuts would be made very close to the desired dimensions to save time. After precisely milled down, the fly cutter head would be exchanged for a drill bit clamp so that we could use the Bridgeport's digital XYZ display to position clearance or threaded holes precisely. And as a final step in preparation, their surfaces were roughly sanded for better epoxy adhesion come assembly.

Figure 5.2: *Cube cutting* ***a)*** *using a hydraulic bandsaw to roughly shape the material;* ***b)*** *using a Bridgeport vertical milling station and a fly-cutter head to precisely shape the material.*

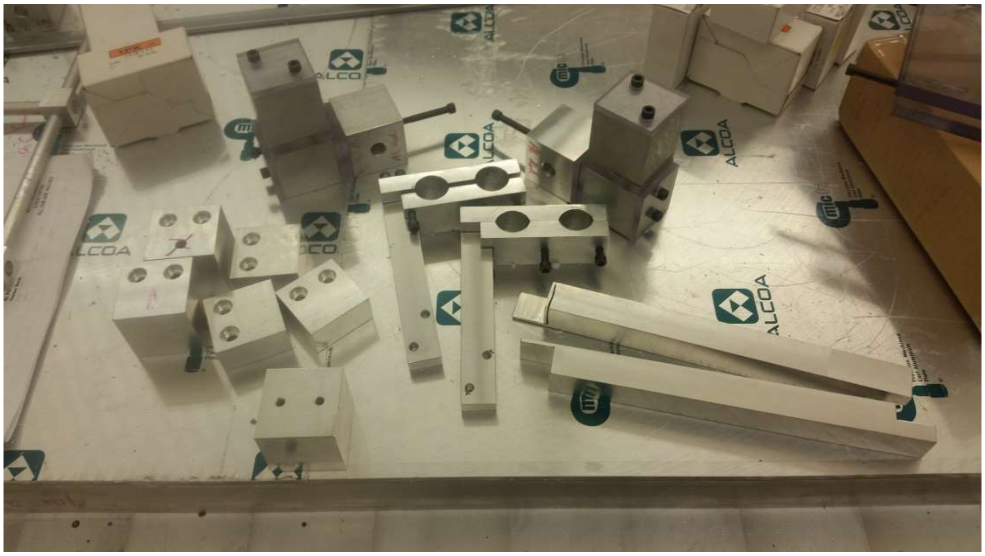

Figure 5.3: *Assorted pieces of aluminum crafted for the TIEC.*

Many of the aluminum pieces composing the BoB's skeletal support structure can be seen in Figure 5.3. On the bottom left are some blocks used as feet for the BoB which screw onto the bottom plate of aluminum with countersunk holes in their bases so the screwheads don't scrape on our lab's tile floor. In the middle and to their right are the two clamp arms that will be bolted onto the BoB's sides and will clamp to the pipes which are bolted to the wall of our lab. The bars to their right were part of a since-scrapped concept for strengthening a weakness in the structure. On either side of the center line to the top of the image are two sets of the aluminum corner cubes to be set in each corner of each box for each side of the BoB (4 blocks per box, and 6 boxes for the sides of the BoB, makes 24 corner blocks in all). These cubes have threaded and clearance holes for the ¼-20" hex head screws fixing many of the pieces together.

Figure 5.4: *Partially assembled aluminum skeleton of the TIEC.*

Figure 5.4 depicts the four 2ft x 2ft x ¼” aluminum plates designed to span the back surface of the BoB laying on top of the Thermwood vertical table mill with some of the corner blocks secured to it and support beams for the stave in place. After the completion of almost each step of fabrication for the aluminum pieces (sets of corner cubes, new holes made for rails to sit in, rails finished, improvements made to other pieces, etc.), we would then assemble more and more of the skeleton, making sure everything fit together nicely and evaluating the overall integrity of the design. Since the screw holes were positioned as though there was between a ¼” and a ½” of polycarbonate between many of the aluminum pieces, at this stage of assembly I cut out about forty 2” x 2” x ¼” polycarbonate spacers then drilled clearance holes in each to stick in between the pieces in place of the as-yet uncut full polycarbonate panels to make certain the blocks would sit in the correct positions while testing their fits.

Figure 5.5: *The aluminum brackets used to secure the TIEC to the wall pipes.*

As the BoB must not only support itself and any test equipment but also remain steady so we can make precise (±0.005in) displacement measurements on the stave’s surface for measuring any deformation, we chose to somehow attach the BoB to a fixed point in our lab. The first idea was to bolt it into a wall, but we realized that would be more permanent that we intended. Our next thought was support beams stretching out from the BoB, but we reasoned they would be in the way of moving and working around the BoB while using it. Then we decided to fabricate the simple aluminum clamp arms depicted in Figure 5.5 to firmly grasp the gas and water supply pipes on the walls of our lab. We could make sure their height on the BoB and the distance they held the BoB off the wall were adjustable, and remove them to reposition the BoB at any time with minimal effort.

Figure 5.6: *The TIEC aluminum skeleton clamped in place during a test of structural integrity.*

We tested whether the aluminum structure could stand freely (which it could, albeit slightly wobbly), then checked to see how stable it was when secured to the wall properly, as seen in Figure 5.6. We were pleased to find that the stability was satisfactory. Even with the wobble caused by insufficient support at the base where the back panels join the base, the clamp arms served to provide adequate steadiness. Therefore it was reasoned that after the wobble was reduced the clamp arms would have no difficulty holding the BoB steady.

Figure 5.7: *Additions to TIEC design;* ***a)*** *triangular brace for the bottom corner of the TIEC, first model of polycarbonate;* ***b)*** *newest model of triangle brace made from aluminum.*

During construction of the aluminum skeleton, we noticed that it had a very pronounced sway and was bending at the bottom corner significantly since the backside L-Beam supports stops 12” from the bottom corner (where the plates on the back surface come down to rest on the base board, along the rear edge of the BoB). We had anticipated that the aluminum backing and base board would be more rigid, and did not want to place too much strain on the polycarbonate structure. Therefore we elected for an add-on consisting of a pair of triangular plates to be screwed into the sides at the rear bottom of the BoB. The first constructed model for the triangular brace was made of polycarbonate and worked well to reduce the sway, shown in Figure 5.7a, but the material wasn’t sturdy enough for the screws to keep from stripping their holes and thus become looser. So another brace was made out of aluminum, shown in Figure 5.7b, which worked well to reduce sway.

5.3 Polycarbonate Sheet Construction

Figure 5.8 depicts the shapes of polycarbonate cut from the 4ft x 8ft sheets that will all become side panels to the boxes which in turn form the sides of the BoB. I hadn’t learned how to operate the Thermwood vertical table mill at the time we received those large panels, and we wanted them cut quickly because we didn’t have the appropriate storage space available for such large sheets. So an experienced machinist named Charles Brown in the workshop was the one to make these particular cuts.

Figure 5.8: *Polycarbonate sheets cut into panels by Thermwood Vertical Mill in the Physics Department Machine Shop.*

After completing most work on the aluminum structure, we moved on to finishing the fabrication of the polycarbonate facings. Mainly, we had to add clearance holes and mill out spaces for the polycarbonate side ports and such. The first step to this process was to convert the 3D CAD model into 2D layouts of the dimensions and locations of all the holes and such. We used KeyCreator's own function for creating these templates, shown in Figure 5.9, to add particular dimensions and text to, choosing how to lay out each piece and the placement of the dimensions. The next step was to print out all the different specifications of the pieces, taking much care to be sure each piece is represented correctly as many are the same size and shape but could have different hole layouts.

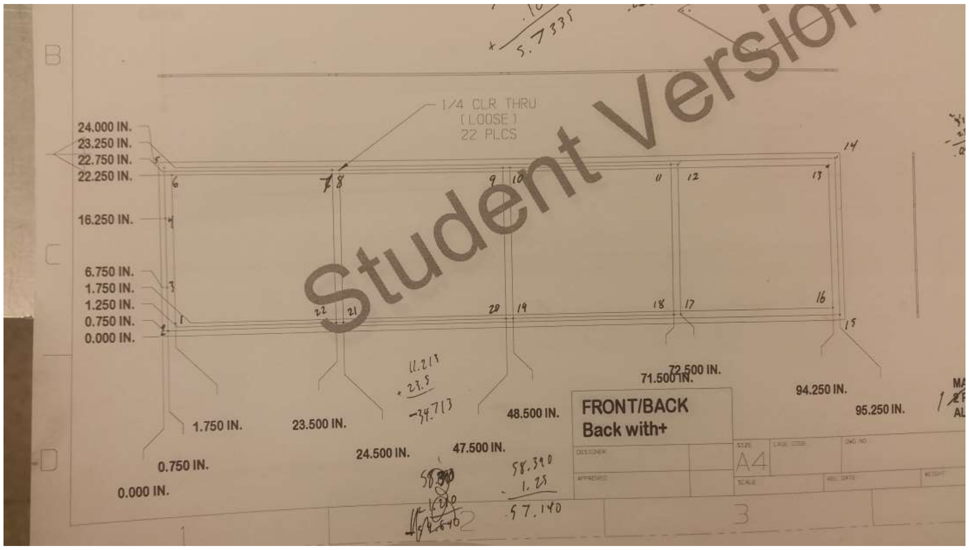

Figure 5.9: *Hole locations for one of the polycarbonate sheets based on the CAD KeyCreator model of the TIEC.*

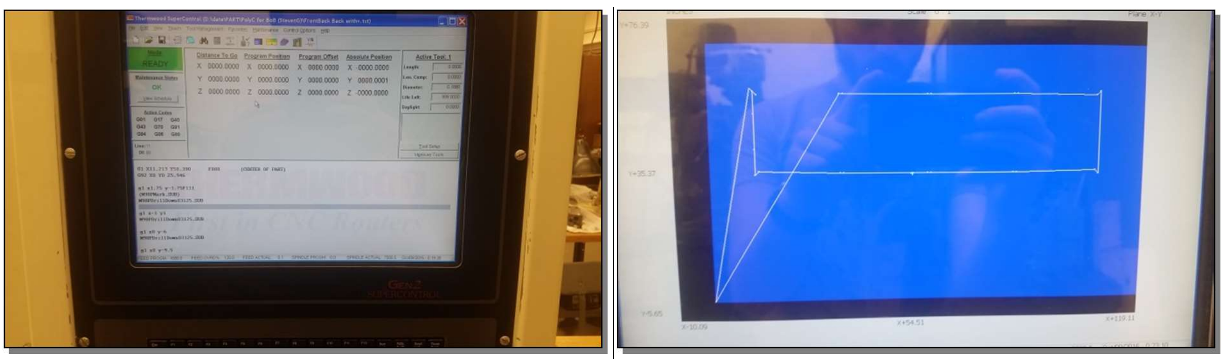

Figure 5.10: *Programming procedure for Thermwood Vertical Mill to drill holes in the Polycarbonate sheet;* ***a)*** *main screen listing current arm position and displaying a code program at the bottom of the screen;* ***b)*** *visual plot of cutting arm's path over the table.*

The third step was to write the program to run on the Thermwood table mill. The Thermwood table mill operates both manually and via a written code program. Figure 5.10a is an example of the format used in programming a path for the cutting arm. In the right is a digital representation of this path (for this path, the dots at each angle of the path are clearance holes in the Front Box's front panel). Each line in the code is input one at a time as single whole commands. Commands can be straight line moves in XYZ to cut along an edge or down to bore a hole, circular paths that can be used to mill large holes or shape curved edges, or more complicated maneuvers which I did not learn as we had no need of them. A major challenge during this step was checking the programs for errors. This is a top priority task, as making repairs on the Thermwood is incredibly expensive and it is a powerful machine that can in fact be improperly handled. I would have to carefully read over the codes and try to spot errors where the tool diameter wasn't accounted for or the arm hasn't been told to move upwards out of the material before moving to the next location for boring a hole, and then change the program to run the tool above the piece, or "cut air," while watching the path it follows to judge if any calibrations need to be made.

Figure 5.11: *Thermwood Vertical Table Mill cutting out the Polycarbonate sheet to size and drilling holes in their proper locations.*

In Figure 5.11 we can see the Thermwood readied to mill the sheet that serves as the door's largest panel. This piece will be having a pair of ¼" diameter holes put in each corner and then three holes 4” diameter bored out from a location ¾ of the way up the panel, at the center, and ¼ of the way up as well. Before running each program, I would need to position the piece to be cut and find the origin. The programs are all written as moves relative to an origin located at one of the corners of each piece, but that origin’s default is the starting position of the arm (off to the side in Figure 5.11). This means I need to figure out where the piece’s origin corner is, relative to the starting position of the arm, and compensate for this offset in the programs. The process involves making a “nest” by sticking small metal dowel pins into the positioning holes of the Thermwood to use as pegs for resting the pieces together, which allows for quickly switching out each cut piece for the next blank and knowing the positions are the same and the piece has been squared off on the table. After the pins, I would clamp down the piece, being careful to make sure I don’t put them somewhere that will be in the way of the cutting arm since a collision with them could seriously damage the precise arm.

Figure 5.12: *A dry assembly to check that all screw holes line up and pieces are the proper size before finalizing the assembly with epoxy.*

Figure 5.12 depicts assorted images of the dry assembly process we did after finishing with the polycarbonate sheets, called “dry” for the lack of epoxy. This was carried out to ensure once everything was in place that the plugs fit into their respective ports, all the clearance and threaded holes between the various polycarbonate panels and the corner cubes line up and allow screws to be tightened in, the stave support bars fit in, and to get a familiar feel for how the assembly process should be ordered.

5.4 Final Assembly

Once all the pieces were done being fabricated, then dry assembled and disassembled, it was time to begin the final stage of assembly: the polycarbonate panels will be acrylic cemented to fuse together, the aluminum cubes will be epoxied into their corners, and everything will get bolted together. Easier said than done. After disassembling back down to just the aluminum back plates and base plate, but before starting to reassemble, I had to build a rig to raise the BoB up from the workspace so that the underside was accessible to clamp arms and to screwdrivers. Figure 5.13a shows the Easy-Angle rack, a simple rectangular prism, sitting under the BoB and on top of the cart used to transport the BoB. It was on this cart that the BoB was reconstructed from the ground up, as seen in Figure 5.13b.

Figure 5.13: *Preconstruction preparations;* ***a)*** *we needed to have the TIEC raised from the work surface to access the underside for clamping purposes so a simple Handy-Angle rack was assembled;* ***b)*** *built from the ground up.*

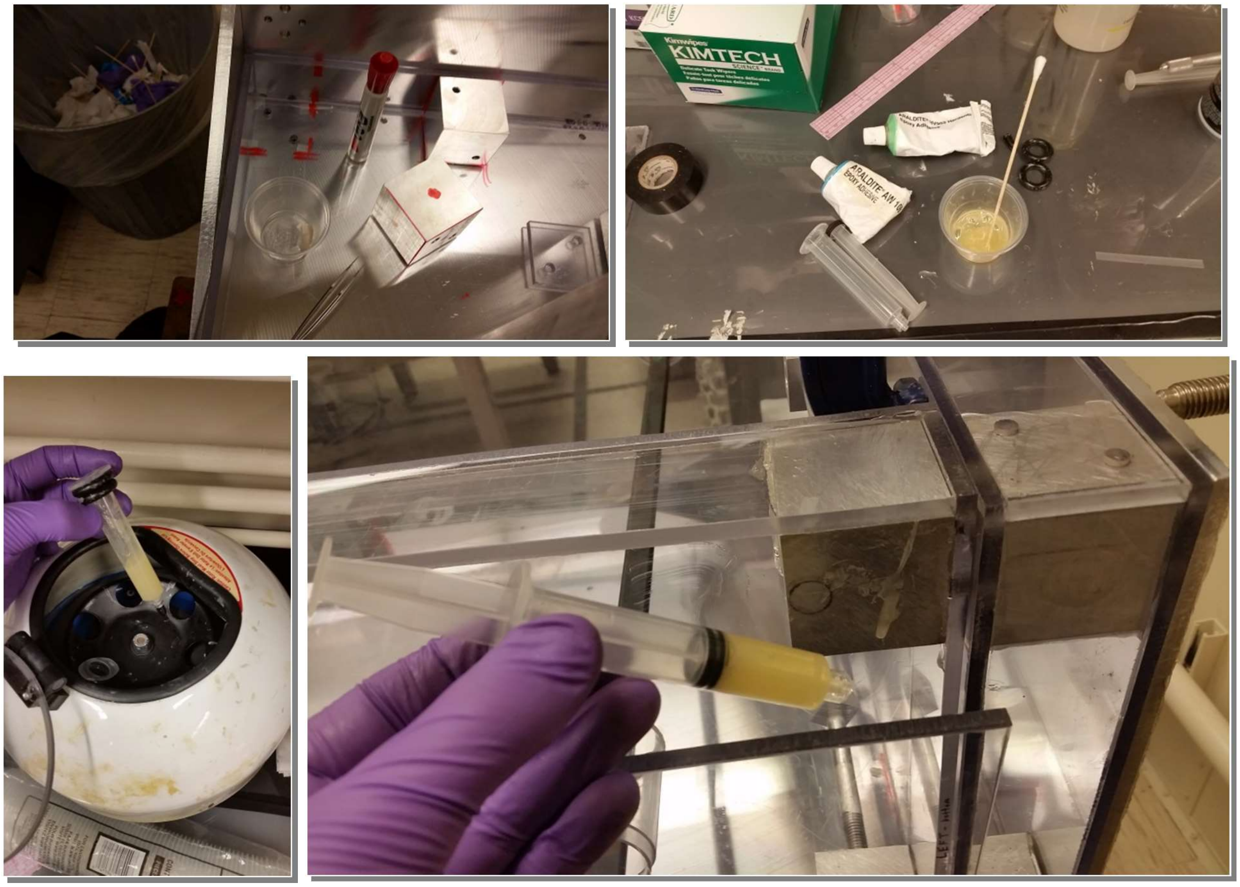

Figure 5.14: *Pre-epoxy prep;* **a)** *marks with dry-erase marker for where to set the plastic spacers;* **b)** *mixing Araldite epoxy as 1:1 ratio;* **c)** *fill syringe with epoxy, cap it, run it in a centrifuge briefly to remove unwanted air pockets from liquid epoxy;* **d)** *epoxy is applied onto blocks' sides and the block is carefully maneuvered into position so as not to disrupt placement of spacers.*

The assembly technique involved a lot of carefully planning the order in which actions must be taken, since each step is making a permanent change to the construct and it would be too simple to accidentally fuse the last polycarbonate panel on one of the sides only to realize I haven't epoxied the corner cubes into it yet. Planning was also necessary to avoid any misalignment problems, as I could use previously constructed forms to hold the next form in place and square.

After I'd written up a construction itinerary, it was time to start gluing. The first step here involved marking where the cubes would each sit and placing 5mm x 5mm spacers that are

0.01in thick at each cube's corner, as Figure 5.14a depicts. The spacers were there so that even when the cubes were tightly clamped there would be some room for the epoxy to sit between the surfaces. The epoxy needs a minimum amount of separation between two faces for proper molecular adhesion. Figure 5.14b shows what's next, mixing Araldite in a 1:1 ratio within plastic cups using cotton-tipped wooden applicators, and then transferring the epoxy to one of the pictured syringes. Then a cap is put on the spout of the syringe and, as Figure 5.14c shows, we put it into a centrifuge to remove as many of the air pockets and bubbles that formed during mixing as we can. This serves to smooth out the epoxy and form a better bond between the surfaces. Once that is done, we can take out the syringe and use it to apply the epoxy to the correct sides of the cube then stick them into place.

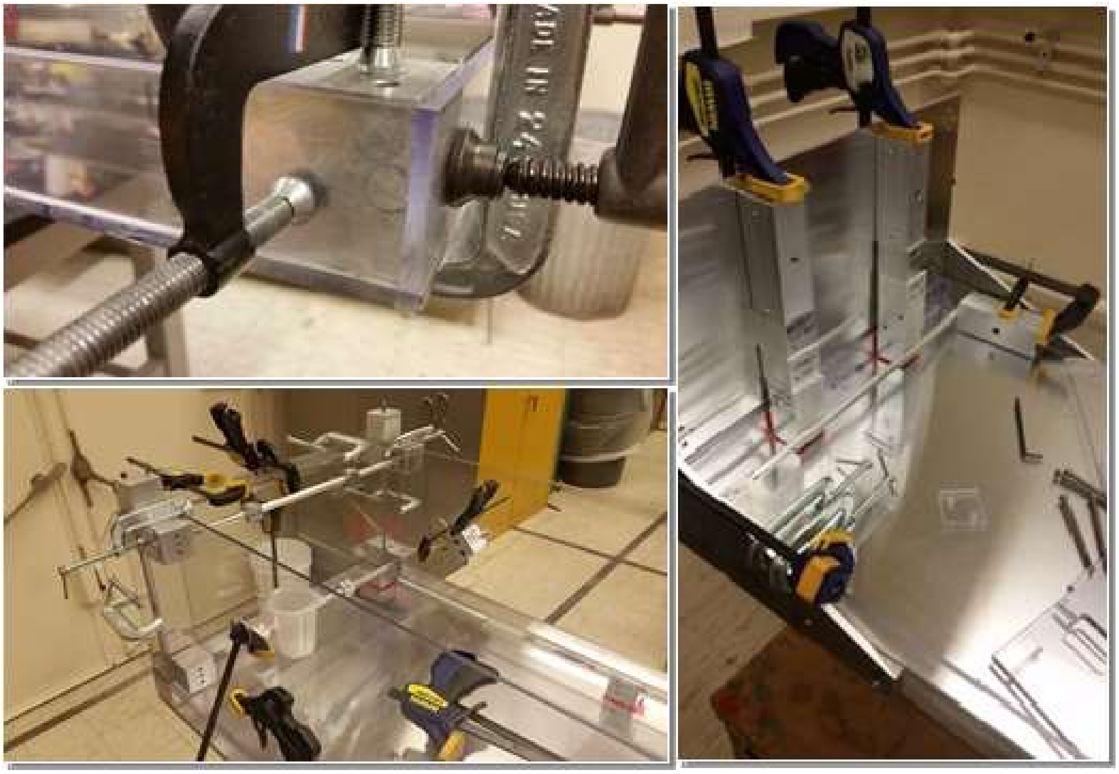

***Figure 5.15:** Clamping techniques; **a)** clamping after blocks and spacers are checked to be placed correctly, blocks are clamped down against each contacting surface's normal axis; **b)** some innovative clamping arrangements were necessary thanks to the insufficient reach of the clamps we had on hand; **c)** another inspired clamping arrangement.*

Once the cubes were in place, I used 5 long-armed Quick Clamps (yellow and black), 4 short-armed Quick Clamps, and an assortment of different-sized spiral carpenter clamps to fix them in position. In Figure 5.15, there are depicted several instances of my clamping techniques, of which there were many strange and inspired configurations. Figure 5.15a shows a standard clamp orientation for fixing an easy-to-reach cube into a corner. But as Figures 5.15b and 5.15c depict, not every cube was so easy to reach with normal clamps. This lead to the need for stacks of spare parts and oddly levered rods to be positioned and clamped down so that pressure could be applied against every epoxied side of every cube. Once the cubes were epoxied and fixed in place they were left overnight for the epoxy to cure.

Figure 5.16: *Process of assembly:* **a)** *First section assembled was the Back;* **b)** *after the Back was the Top, and the Bottom was also added while the Left and Right were positioned to help assure the Top was cemented without slant or misalignment;* **c)** *then the sides were acrylic cemented together on a nearby work surface;* **d)** *once five panels of both the sides were cemented together, the ports were added and cemented, then the corner cubes were epoxied and clamped in place;* **e)** *with the cubes in place, the Back, Bottom, Top, Left, and Right sides could be screwed together as the Left and Right dried;* **f)** *the Front is cemented together on the other workspace and the door components along with the corner cubes are epoxied in place;* **g)** *the epoxying and acrylic cementing is complete for the TIEC.*

The general order of assemblage for the six sides of the overall BoB was: Back, Bottom, Top, Left, Right, and Front. For the Back, I first had to take off the extra six support cubes along either side at each joint of the four 2ft square aluminum back panels, as the cubes were already in place because they need to hold the panels together. Once they were off, I added the largest polycarbonate panel and the four 2" wide side pieces to serve as the Back's top, bottom, back, left, and right, then replaced the six support cubes and added in the four corner cubes to use as guides for the flexible polycarbonate pieces. When everything was in place, I clamped the polycarbonate pieces just hard enough to press together the faces to be fused and used a glass syringe with a metal tip to apply the acrylic cement. It dried within ten minutes, and I released the clamps. Next, I marked up the cube positions, added the spacers, mixed epoxy, syringed it onto the cubes, stuck them in place, clamped them down, and wiped up any extra epoxy that squirted out of any joints. The next day, I removed the clamps, trimmed any excess epoxy globs, and began attaching the front panel of the Back side on. First I added epoxy and spacers to all the cubes, then placed on the front panel to clamp down on the epoxy, and finally fused the polycarbonate together. Figure 5.16a depicts the state of the BoB at this stage.

A day later, I added on the large bottom panel and the 2" wide left, right, front, and back panels to form the Bottom side. The cubes were positioned and everything was clamped in place, then the polycarbonate was fused and dried, and finally epoxy was added to the cubes. At this point I began to use other cubes and some screws to help fix the ones being epoxied into place, so I had to be very careful about not letting any epoxy run into the threads of the screws since I would later want to remove the extras. As the epoxy on the Bottom cubes dried, I began to assemble the Top. The Left and Right sides weren't together yet and I needed guides to align and square up the Top with during its assembly, so I decided to add the Left and Right's large inner polycarbonate panels for squaring the Top, their corner cubes to help align and clamp the epoxied cubes down, and the aluminum rods to space the Left and Right apart. As with the previous sides, first the Top was assembled with all pieces and cubes except for one of its largest faces, then its polycarbonate was fused, and finally the cubes were epoxied in. After a day of curing, the Top and Bottom were ready for their final panels of polycarbonate. This involved removing the parts for the Left and Right sides, adding spacers and epoxy to the Top and Bottom's cubes, placing their panels on, then replacing the large sides and the cubes for the Left and Right to help align and clamp everything. The BoB at this stage is depicted in Figure 5.16b.

The next sides up for assembly were the Left and Right, which were somewhat more involved as they additionally have the seven ports to go in each. These sides were cemented and epoxied on a workspace separately from the rest of the BoB since the clamping configurations to properly press the pieces (especially the cubes in the back corners, which sat a foot deep inside the main compartment of the Bob and out of reach from the clamp arms) would've been needlessly complicated and unreliable if they weren't separated. So as Figure 5.16c depicts, five of the polycarbonate panels for the Left and Right were clamped together with their cubes in place and were acrylic cemented at the same time on a table next to the BoB. After the cement dried, epoxy was applied and the cubes were clamped down and left to cure. The ports were added the next day with the help of the sixth panel being used to assure the ports would dry straight, and they were cemented to the side with cubes already. I did not cement the ports to the sixth panels because I wanted to epoxy and fuse those panels on when the Left and Right were in place on the overall BoB so that I could check their fit before finishing those sides. Figure 5.16d depicts the state of the BoB as I was adding on one of these nearly complete sides, and Figure 5.16e is an image taken as I screw together all the sides. After the Right and Left (incomplete) were added to the BoB, I put epoxy on their cube surfaces and clamped the final panels onto them then acrylic cemented their outer edges. I didn't have enough clamps for cementing the ports on in the same day, so since the epoxy takes much longer to dry the ports could wait until a more convenient time.

Figure 5.17: *Standing the TIEC and attaching to the wall;* ***a)*** *stood on top of a sheet of cardboard to allow for sliding on the tiled floor to position it, and strapped in place with bungee cords;* ***b)*** *the clamps are mounted on the wall pipes, wrapped several times around with electrical tape, then the TIEC is bolted to the clamp arms and through the back aluminum L-beam.*

The final side to assemble was the Front. As the acrylic cement solution was the viscosity of water and thus could easily run down, I decided that the best course again would be to assemble the side separately from the rest of the BoB. Figure 5.16f depicts the Front being assembled on the nearby table, nearly complete with its cubes already epoxied in place along with the aluminum edge blocks for the door structure and the large door ports cemented in.

Figure 5.16g shows the BoB after the complete assembly of every side, the cementing together of those sides to each other to make it airtight, and the addition of the Front side.

Once all the sides were assembled, the BoB was ready to be stood up and have its final touches applied; namely: the wall clamps, door handles, and door guide pins. The BoB was slid off its work cart and onto a cardboard sheet to let it slide easier over the tiled floor, then brought over to the wall we would be attaching it to and bungie corded to the pipes to avoid the risk of it tipping over while I bumped and jostled it to affix and position the wall clamps. The pipes were wrapped around about 10 times with black electrical tape to provide the clamps with more friction since they'd originally been fitted to larger pipes elsewhere in our lab and thus did not make good contact with the new pipes. In addition to the clamps being improperly sized, they were also not attached to the same position on the BoB. Luckily, we'd formed a contingency plan for just such a case and had made the clamp arms with slots to be more adjustable. So all I had to do was attach one of the clamps to the wall, move the BoB over to it, drill two holes through the BoB's back L-beam, bolt the clamp arm to the BoB, then attach the second clamp to the pipes on the other side and repeat.

Figure 5.18: *Final touches;* ***a)*** *there is a block of wood to lift and set the heavy door on to let it rest on while lining up the pins;* ***b)*** *the door cube alignment pins in each corner help with lining up the clearance holes in the door's cubes with the threaded holes in the TIEC's cubes, and the aluminum stave-mounting plate.*

After the BoB was properly positioned in the lab and attached to the wall, the last task to complete was in finishing the door to get it to work properly, that is capable of being removed and reattached by a single person with average size and strength (as judged by me, a 6' male of 180lbs). The door is somewhat unwieldy thanks to its weight and size, therefore it would be difficult to properly align the door's clearance holes, and thus the screws, with the case's threaded holes since the inner surface of the door sits against a flat, vertical, and smooth surface with its bottom face 2¼ inches off the ground. My solution, as depicted in Figure 5.18a, was a wooden block cut to be 2¼ inches tall on a table saw, and the door alignment pins depicted in Figure 5.18a and 5.18b. The pins were 3" long screws with ¼-20" threads left over from assembly with their heads cut off on a bandsaw and sanded to be round-tipped, which were then clamped with pliers and tightened into the four outermost threaded holes in the case.

Figure 5.19: *The TIEC as it now stands, complete with door handles and ready for use.*

The BoB has now been completely assembled, the door is able to be removed and attached with relative ease. It is ready for use.

Chapter 6:
Validation of the TIEC

In this chapter, we present our assessment of the TIEC concerning its performance. We revisit our preliminary requirements, explain the procedures for appraisal and results we obtained therein, and conclude on the project's merit.

6.1 Recap of Requirements for TIEC

The sensors should be cooled to temperatures below -5ºC when being operated within LHCb, so a CO_2 cooling system was integrated with the stave. In order to identify areas for improvement to maximize the stave's efficiency, I was assigned to design and construct the Thermally Insulating Experiment Case (TIEC). The experimental setup's thermal requirements were to (1) thermally isolate the stave no worse than the Pink Panther setup from the warmer lab air to simulate the closed environment in LHC, (2) to be compatible with the cooling system's inlet/outlet, (3) achieve stave temperatures of -30ºC, the nominal temperature of the CO_2 coolant, and (4) hermetically seal out humidity to prevent ice accruing on the sensor equipment. Mechanical requirements included: (5) appropriate internal dimensions to accommodate three staves side-by-side and match their vertical orientation, (6) use of a clear, strong material for the stable fixture and inspection of internal mechanical deformation measurement apparatuses, (7) a metal support frame to strengthen the main polycarbonate case structure, (8) an internal support structure to stably suspend the staves, (9) small-gauged side ports allowing power (heat) cables and data readout wiring internal access, (10) medium-gauged side ports allowing coolant tubing internal access, (11) large-gauged front viewing ports allowing infrared imaging, and (12) a lid or door that can be removed and reattached with relative ease.

6.2 Mechanical Evaluation

I've used a Computer Aided Design (CAD) program to design a thermally insulated eight foot tall, two foot wide, and one foot deep box using panels of the strong and transparent thermoplastic polycarbonate laminate and aluminum blocks, rods, and panels. The models were fabricated, incorporated into the partially produced construct, redesigned, and fully assembled with fastened screws, fused polycarbonate panels, and cemented epoxy.

Upon completion, we observed and confirmed that many of the initial mechanical requirements have been fulfilled. The internal dimensions have been confirmed as practical for both the staves and any mounting apparatus. Enough space inside is available for three staves while leaving room for the experimenter to make their adjustments while suspending them. The plan to make panels into cases with sealed air volumes and assemble them into the larger case was sufficiently structurally sound upon realization. The sides all fasten together snuggly and appear as they were modeled. The aluminum frame offers excellent reinforcement with the additional redesigned braces, and fastens the BoB unwaveringly to the lab room’s wall. Its location in the lab allows for the cooling system to be nearby, and is also close to the computer where we collect the temperature readout data. The side ports were appropriately sized to accommodate the coolant inlet/outlet tubes and the dozens of RTD wires, and suitably positioned to allow access to a variety of locations along the stave. The door handles are well-placed and sturdy enough to allow maneuvering the lid with relative ease, and additional revisions were enacted to further assist in its attaching and removal.

However, several requirements for the mechanical performance were not as well-met. The front view ports are somewhat smaller in diameter than we would prefer as their depth doesn't allow for thermal imaging beyond the section of the stave directly beyond them. The mounting of the full stave could not be evaluated, however the stave components for fastening to the suspension structure had their alignments checked and are confirmed to fit, therefore we assume the full staves can be properly mounted. This also meant we could not appropriately evaluate the power/coolant service measures, but they were properly included in the construction as per our design specifications.

6.3 Thermal Evaluation

To evaluate the BoB thermally, we performed several mock cooling trials. Low temperature techni-ice packs at -25^{o}C were placed inside the BoB, the door was bolted shut, and a series of images were taken with a Fluke brand thermal camera.

The ice packs were placed inside against one wall and isolated from the rest of the BoB with styrofoam. RTDs were placed against the outside surface, and between two of the sheets of ice packs. This situation is shown in Figure 6.1. With the door shut we would be able to assess through the Fluke camera the thermal behavior in real time with broader and more easily interpretable results than had we used RTDs to monitor multiple points.

Figure 6.1: *Arrangement of ice packs and RTDs around TIEC;* **a)** *placement of RTDs;* **b)** *added ice packs against inner side of TIEC with internal RTD between;* **c)** *thermal image of ice packs before sealing TIEC.*

Figure 6.2 depicts a thermal image taken towards the end of the evaluation, and exemplifies the thermally reflective properties of polycarbonate with the thermal "image" of me. This presents a problem for imaging internal structures and drove our choice for adding view ports on the front.

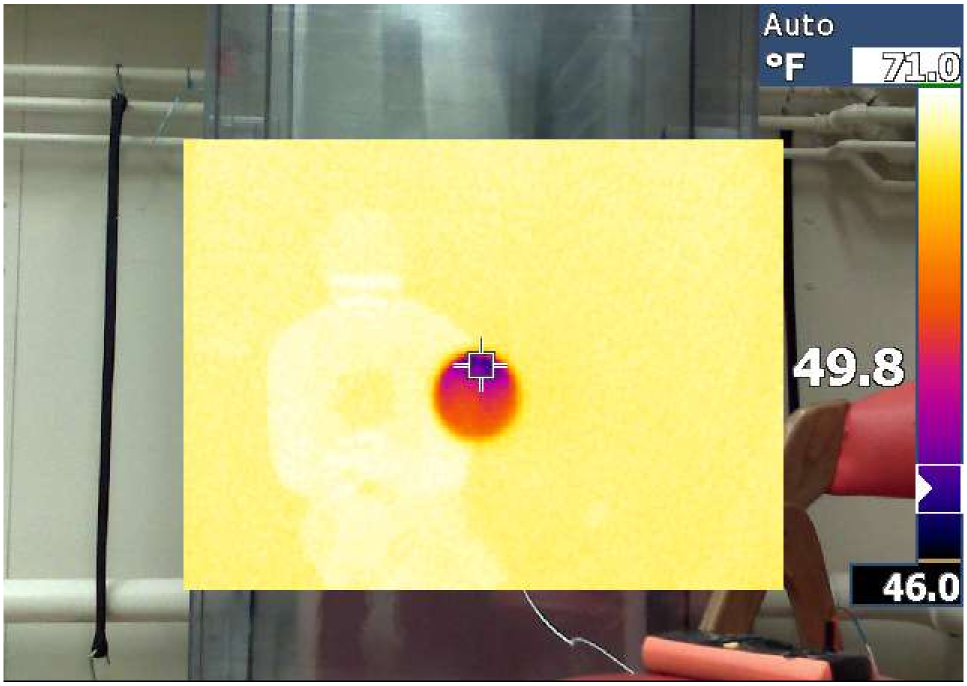

Figure 6.2: *The polycarbonate has thermally reflective properties, making external thermal imaging of the stave difficult.*

We used the thermal camera to diagnose temperature leaks and monitor the case's overall exterior temperature while the ice packs were cooling the inside. Figure 6.3 depicts our three main areas of interest from various angles and with different temperature readout locations. In 6.3a, the center-screen cursor is over the panel directly outside from where the icepacks are contacting the interior surface. In 6.3b, the camera is aimed at the lowest front port which was left open during imaging to check on the ice packs, pictured in 6.3c with the camera aimed up through said port. 6.3d shows the gap we have in the BoB between its lid and the left edge of its main case. We will be resolving this issue with adhesive insulating foam to provide a rudimentary seal around the lid.

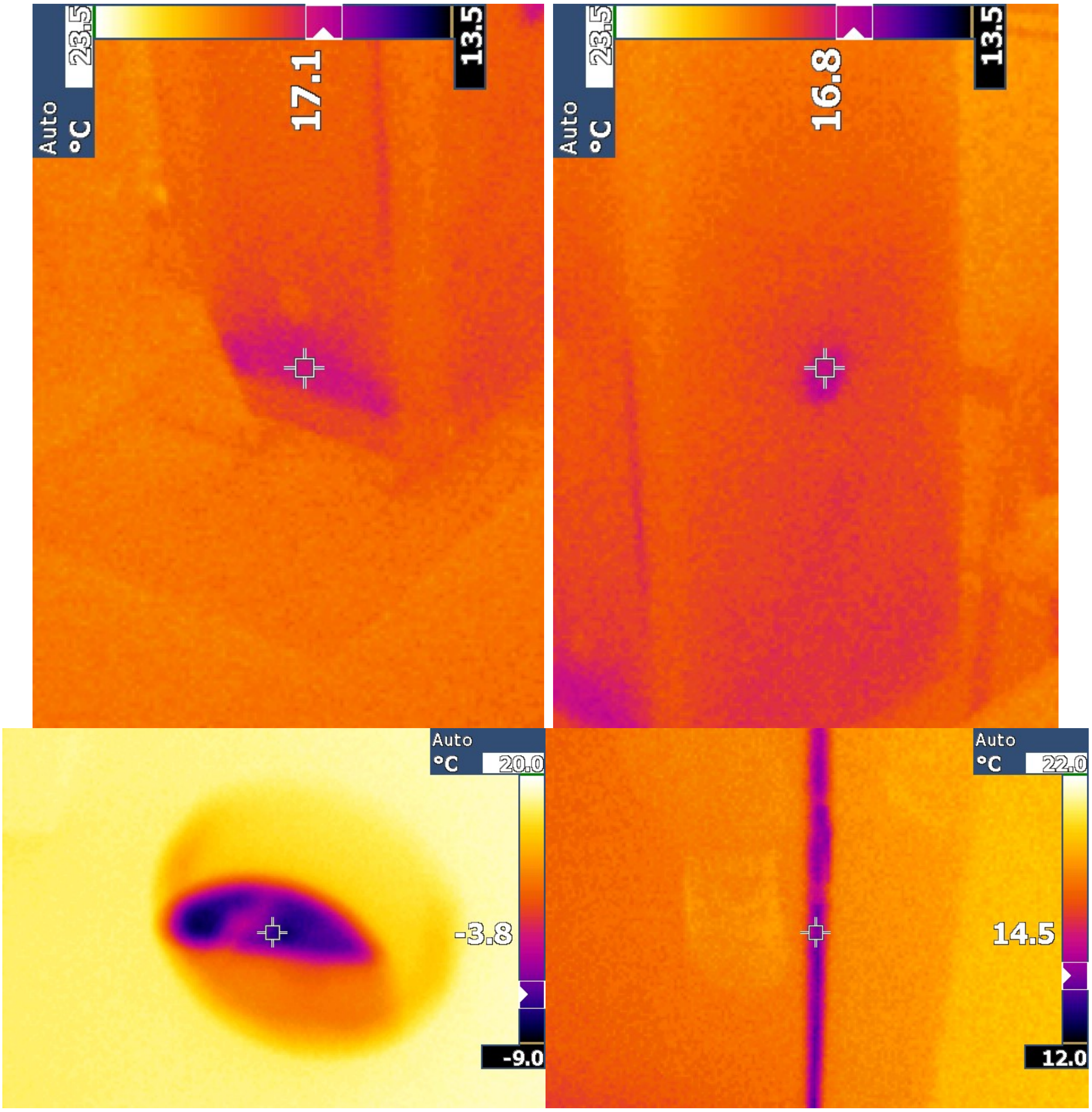

Figure 6.3: *Various thermal images of the TIEC during thermal evaluation;* **a)** *the surface of the TIEC exterior to the ice sheets placed against the inside;* **b)** *an open viewing port on the front of the TIEC;* **c)** *a view through the open port of the ice packs inside;* **d)** *a gap between the door and the main body.*

We now compare the Pink Panther's insulating performance with that of the BoB, specifically by calculating and comparing their R-values. A material's R-value is a measure of its thermal resistance relative to its thickness, signifying how effective a thermal insulator it is. Our insulating foam used for the Pink Panther box has a listed R-value of 0.526 $K*m^2/W$ [2], whereas the polycarbonate-air-polycarbonate design has a cumulative total R-value of 2.02 K*m^2/W. Our material's value was calculated from the added R-values for two ¼" thick polycarbonate layers each with an R-value of 0.041 K*m^2/W [6], and one layer of 2inch thick still dry air which has an R-value of 1.93 K*m^2/W [1]. From this comparative analysis we conclude that the BoB is preferable over the Pink Panther test box with relation to thermal conductance.

We ran the thermal evaluation test with the techni-ice cooling the inner surface for two hours, recording RTD temperature readouts every 5 minutes. The accrued data is represented in the Figure 6.4 graph. We achieved a maximum internal temperature difference of -28.3°C, and obtained a stable (hour-long) temperature difference of ~15°C. Based on our readings, the temperature difference seems to be stable over a long period of time. Judging based on the BOB's techni-ice test and comparison of R-values between our older and new setup, we conclude the TIEC to exhibit satisfactory thermal behavior.

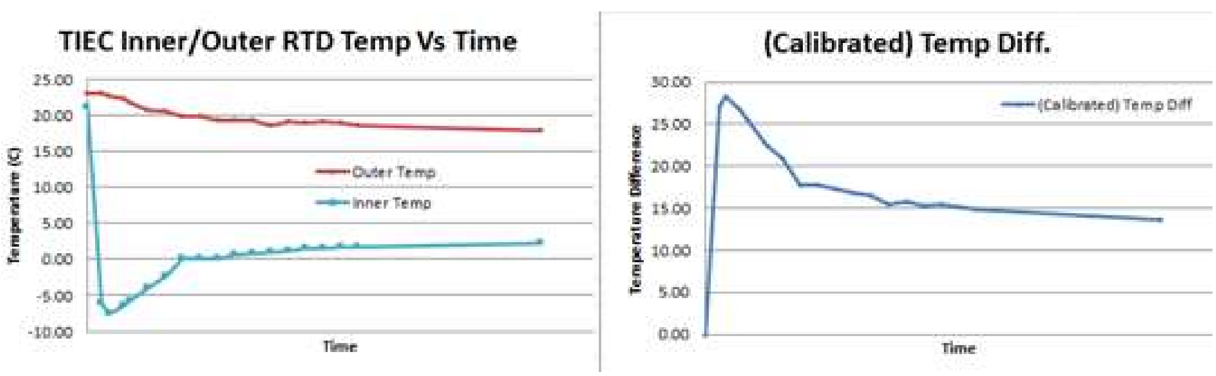

Figure 6.4: *Data accrued and analysis conducted during Techni-ice Test. Full scale for time axis is 2 hours total.*

Chapter 7:
Capstone Summary

In this chapter, I summarize the Capstone project in its entirety. The experimental motivation is revisited, the progression of the project is reexamined, and the conclusions reached by its evaluation are resumed.

7.1 Background Rationale

The Standard Model of Particle Physics is a well-tested theory that serves to describe the fundamental composition and interactions of the universe. A universal mystery left unanswered is the imbalance of matter over antimatter, which may be understood through studying interactions of particles exhibiting behavior which violates the assumed fundamental Charge-Parity symmetry. Their interactions are studied at particle accelerators and detectors, such as the Large Hadron Collider at CERN in Geneva, Switzerland. At the LHC, the LHCb Experiment is principally concerned with such interactions as those with CP-violating behavior.

In the expected operation of the upgraded LHCb's Upstream Tracker subdetector, there is power dissipation over the stave's electronics, specifically the ASICs and silicon strip sensors. The sensors should operate at temperatures below -5ºC. To counteract the heating components, the stave has an integrated CO_2 bi-phase cooling system with liquid carbon dioxide running through thin titanium tubing with a 2.2mm diameter and 0.125mm wall thickness and evaporating to draw heat from the stave. CO_2 is pumped through by a sophisticated closed loop cooling system, and will be held at high pressure.

Any suitable cooling system must be tested and measured before being deemed acceptable. In order to identify areas requiring modification to maximize the stave's effectiveness, our research group had to set about on a process of refining the setup for testing the stave. The experimental setup was required to: provide structurally stable vertical support for up to three staves and thermally isolate from the environment, allow access for power (heat) and coolant to the mock-up/prototype stave, allow measuring of mechanical deformations and temperature accurately and precisely at many points, and allow infrared imaging of the stave. Rather than try to improve the flawed designs of the Pink Panther box in preparation for more quality tests, we decided to build a new thermal isolation test setup from scratch.

The TIEC is built to assist with insulating the stave test samples from lab room air to cool the sample, prevent icing, and physically stabilize test samples well enough to allow precise thermo-mechanical measurements of the stave while not stressing the stave and breaking the electronic wire bonds or restricting its thermo-mechanical behavior.

7.2 From Concept to CAD

I utilized a Computer Aided Design (CAD) program called KeyCreator to conceptualize the TIEC. We wanted 6 containers of dry still air for insulation to form the sides of the overall Box of Boxes, a rigid aluminum skeletal structure for stabilization, a removable door, side ports for coolant inlet/outlet and stave power and data, and front view ports for thermal imaging.

I designed the BoB with appropriate dimensions to accommodate the staves, out of polycarbonate for its thermal properties and strength, seven hollow polycarbonate cylinders for the ports, and a suspension rig to support the staves. Additionally there were the components that made up the aluminum support frame, including: the five panels of aluminum on the back and base, the L-beams down the back sides, the feet underneath, the clamp arms in back, the triangle braces at the rear corners, and the handles and support cross-rods in the door.

7.3 Construction

After designing most of its components, fabrication began to get a feel for any unforeseen complications that would require redesign. Our starter materials were four 8ft x 4ft polycarbonate sheets, a 4ft long aluminum 2in x 2in bar, several rods and tubes of either material, and many screws. The methods of fabrication called for a machine guided vertical milling station, a manual vertical mill, a manual lathe, a drill press, an electric screwdriver and wrenches, a bandsaw, and a belt sander. With these tools we cut rough blanks, precisely shaped each to specs, and checked their fit.

The first components made were for the aluminum skeleton, including the cubes, the back plates, the L-beams, and the support rods for the suspension rig. These were all assembled and upon inspection they lended to uncovering flaws such as insufficient rigidity and misalignments needing correction. Next the polycarbonate sheets had the panel shapes cut out and holes added via the self-written programs for the Thermwood. Once manufactured, the panels were incorporated into the dry assembly to confirm an adequate fit. The complete dry assembly was taken apart, and our final assembly began. I used epoxy to adhere the cubes into their appropriate corners, and acrylic cement to fuse the polycarbonate panels together. Afterwards, the BoB was stood up in our lab, attached to the wall, and made ready for assessment.

7.4 ***Appraising TIEC Performance***

Once the project became ready to use, we compared the design expectations with the finished product. In the end there were a few discrepancies which require future investments to amend. Mechanically, the BoB fulfilled all design specifications objectively. Thermally, the assessment showed good thermal behavior of the TIEC.

Overall, we are satisfied with the thermo-mechanical behavior of our Thermally Isolating Experiment Case and we are now ready to use it to optimize the LHCb UT stave. Thus we have fulfilled the overarching goal of this project and are ready for its use in future measurements.

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