

1 Introduction

This document contains instructions on how to print and assemble your very own mini LIGO model. It does not however include instructions on how to create a Michelson Interferometer so refer to these two links for assistance: LIGO-T0900393 and LIGO-T1400762.

This document also includes notes on the project I have worked on this summer.

This model is a simplified, 1:24 replica of the LIGO telescope. It contains the main structures of the LIGO telescope along with some interior parts. The model includes three BSC Chambers and one HAM Chamber. This document provides all necessary materials which includes: 3D files, instructions for 3D printing, assembly of the parts, diagrams, and pictures.

Additionally, this document contains an update in model design. The model has been updated due to a new addition to the model known as A+. A+ consists of 2 HAM chambers and 1 BSC chamber. Some .stl files have also been redesigned to combine parts, reduce the number of prints necessary, and allow for better 3D printing results. If for any reason the new part files do not work, please refer to the previous version for the original files.

2 General Terms

There are many acronyms at LIGO (Laser Interferometer Gravitational-Wave Observatory) and it's important to know some of them (at least the ones you will be working with).

BSC and HAM Chambers are the two chambers that house optics in the interferometer.

The BSC (Beam Splitter Chamber) houses the beam splitter and the optics at either end of the arms. There are one or two more BSCs in between the beam splitter and the end of the legs but for our purposes we will just focus on the main BSCs.

The HAM (Horizontal Axis Module) is found in the main building where the laser and beam splitter are kept. The laser beam travels many times between HAM Chambers before it reaches the beam splitter.

Other terms you may come across are ISI and HEPI.

ISI (Internal Seismic Isolator) is used to counteract and balance any movements in the ground.

Since the actual interferometers at Livingston and Hanford are so powerful, the slightest disturbance here on Earth can be detected as a wave. The ISI reads and senses shifts in the ground's movement and stabilizes the structures.

HEPI (Hydraulic External Pre Isolator) functions similarly to the ISI. The HEPI however is a larger structure that surrounds the chambers and stabilizes the entire chamber.

3 3D Printing

3.1 Files to Print

Below is the updated list of files for the new A+ addition and the original mini LIGO model. The files are all in .stl file format and can be imported onto most softwares for slicing. These files can

be found on the same DCC page as this document. We have included the quantity of each file to create a full model.

Original model:

BSC Chamber:	HAM Chamber:
BSC Cover (x4) BSC End Cover (x2) BSC HEPI Chamber Level (x3) BSC Lower Shell Middle (x3) BSC Lower Shell Top (x3) BSC Quad for BS (x1) BSC Quad for XY (x2) BSC Top Hat (x3)	HAM 84in Cover (x2) HAM Chamber (x1) HAM HEPI Chamber Level (x1) HAM ISI Bottom (x1) HAM ISI Top (x1)

A+ Model:

BSC Chamber:	HAM Chamber:
BSC HEPI Chamber Level (x1) BSC Chamber (x1) BSC Top Hat (x1) BSC3 Door Type1 (x1) BSC3 Door Type2 (x1)	HAM 84in Cover (x2) HAM 60in Cover (x1) HAM Septum Door (x1) HAM A+ HAM7 84in Cover (x1) HAM A+ HAM8 84in Cover (x1) BSC Cover (x2) HAM Chamber (x2) HAM ISI Bottom (x2) HAM ISI Top (x2) HAM A+ External Support (x2)

3.2 Opening Files in Cura: Slicing Software

A slicing software slices designs for the 3D printer to be able to work layer by layer to create your model. Most slicing softwares use .stl files to create printable models while other softwares also use .thing or .obj files. Many slicing softwares give suggestions on what settings to manipulate but we have provided some suggestions of our own that worked with our prints. I used Cura as the slicing software for my project. It is very easy to use and there are various tutorials online if you are looking to learn more about it. The process of uploading files onto Cura and preparing them becomes rather routine if you set up a custom settings preference. Setting up the printer takes a little bit more work because every setting must be perfect otherwise something might go wrong.

3.3 Programming Cura's Settings for Best Results

It is very important to have the best settings when working with a 3D Printer because much of the success of your print comes from how well you know how to manipulate the settings. Cura has default print settings that you can opt to use until you are unsatisfied with your print or want different results.

Cura has many different categories one can manipulate, and these are the ones we used (I have added brief descriptions of each setting):

Quality: layer height, line width

Shell: wall thickness, this means the outer layer of the print

Infill: density by percentage; if the percentage is greater, the print will be more solid (filled in)

Material: determines the temperature of the extruder throughout the print as well as the build plate temperature

Speed: the speed of print or of individual layers and shells, increasing the speed will not always guarantee a successful print. It may make the print shorter but the quality of the print will go down.

Travel: how much the extruder moves between layers and in between structures

Cooling: controls the fans in the printer and their speed

Support: generates structural support for things that are virtually impossible to print such as arches, or anything that does not build vertically

Build Plate Adhesion: allows the printer to warm up and builds either a skirt or brim around the 1st layer to make sure the extruder is working properly

There are only a few settings that we changed so unless otherwise stated, leave the default settings on all of the other options.

Quality:

Layer Height	0.2 mm
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Shell:

Wall Thickness	1.2
Wall Line Count	3

Support:

Generate Support	Checked (this system automatically generates supports and other settings under this category)
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Build Plate Adhesions:

Build Plate Adhesion Type	Brim
Skirt/ Brim Adhesion Type	250 mm
Brim Line Count	8 lines
Brim Only on Outside	Check
Brim Width	3.0 mm

3.4 Updated Estimated Time of Prints

Below is the updated estimated times for each print (not including 2 or 3 copies of one print). Many prints do take longer than estimated so allow extra time in case the print runs long.

BSC Part	Estimated Time
BSC Cover	55 mins
BSC End Cover	50 mins
BSC3 Cover Type1	43 mins
BSC3 Cover Type2	43 mins
BSC Quad for BS	7 hrs 45 mins
BSC Quad for XY	8 hrs 20 mins
BSC HEPI Chamber Level	18 hrs
BSC Chamber	15 hrs 25 mins
BSC Lower Shell Bottom	3 hrs 52 mins
BSC Lower Shell Middle	6 hrs 8 mins
BSC Lower Shell Top	2 hrs 20 mins
BSC Top Hat	10 hrs 31 mins

HAM Part	Estimated Time
HAM 84in Cover	1 hr 55 mins

HAM7 84in Cover	1 hr 56 mins
HAM8 84in Cover	1 hr 57 mins
HAM 60in Cover	59 mins
HAM Septum Cover	39 mins
HAM Chamber	14 hrs 28 mins
HAM ISI Bottom	1 hr 22 mins
HAM ISI Top	4 hrs 1 min
HAM A+ External Structure	2 hrs 43 mins
HAM HEPI Chamber Level	7 hrs 39 mins

3.5 Before the Print

When you have sliced your file and are satisfied with the settings you can then export the sliced file and either save it as a file or save it onto a removable drive such as a USB. The completed, sliced file is saved as a G-Code file, ready for the printer. If you save it onto a USB, you can then plug it into the printer and begin printing.

3.6 Setting Up the Printer

Every 3D printer is a little different but for the most part they all function the same. You may want to consult your printer's manual to know where all of the buttons are and what they mean. We have provided instructions on how to setup a printer. We used the CraftBot Plus 3D printer.

1. Heat the Extruder (nozzle) and bed.
2. Align all sides of the bed.
 - a. Some printers have 3 points to align and some have 4.
 - b. Make sure you can slide a card snugly between the extruder and the bed. If the extruder is too far from the bed the first layer of your print will not stick to the bed and will mess up the rest of the print. If the extruder is too close to the bed it can damage the extruder and creates a very rough first layer. If your printer creates a rough first layer and it is not smooth, stop the print otherwise the extruder will get clogged and break.
3. Once the extruder is heated properly, you can then reverse the filament to extract it from the extruder and change the filament color.
4. Once you have inserted the filament/color of your choosing, extrude the new filament to ensure that all old filament has been extruded from the nozzle.
5. Press the XYZ House button to recenter the extruder.

6. Finally insert your USB into the printer, press the USB icon, select your file, and press the icon.
7. Wait for the first layer of the print to be completed before leaving to ensure that everything is running smoothly.
 - a. This is crucial because there are many people that leave once they have set up the printer and their first layer is not always good.
 - i. This is where you can spot whether the extruder is too close or too far away from the print bed.
 1. If you do not fix the problem above, it can also lead to collapsing supports or filament tangles among other things.
 - b. If your print fails in the first few minutes, do not be afraid to stop it and start over. It is better to start over at the beginning than to come back hours later, see a disaster, and have to reprint the entire thing again.

3.7 The Process of Printing

Every project brings about several obstacles which set things back and call for redesigning, retesting, and essentially reprinting. During my time here at LIGO I realize how many things can go wrong because of one little thing. 3D printing is a relatively new technology and since it is so new, many of the softwares and printers are still being tested and cannot guarantee a successful print every time. In fact, with almost every model I printed, I had to print a second one because something always went wrong. At first, it requires a few tries to feel comfortable with 3D printing, but then it becomes easier to spot problems which you can easily fix.

3.8 After the Print

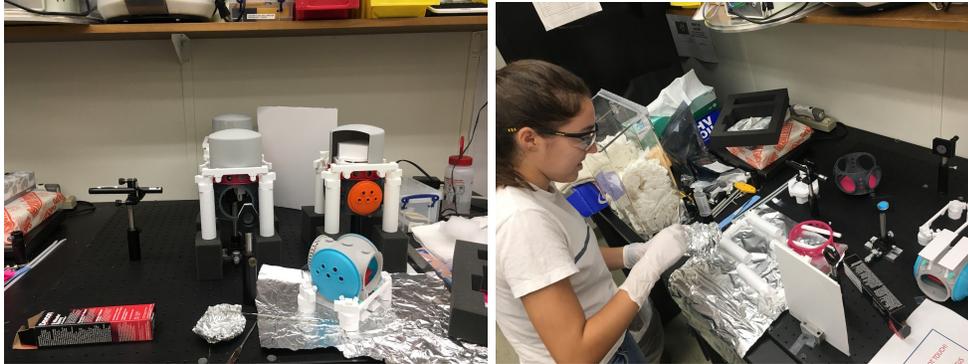
When the print is complete you can pry off the model and begin removing supports. You can remove supports with pliers or other tools. If you have forgotten which parts of your model are supports, you can look back in Cura and turn on layer view. Once you are in layer view, you can select show helpers and it will show you where all of the supports are. Another way to know which parts are supports is when you press them with some force they move and are not as sturdy as other parts. Remove all of your support and finally begin sanding the rough edges to create the smoothest print.

4 Assembling the Model

4.1 Gluing Structures Together

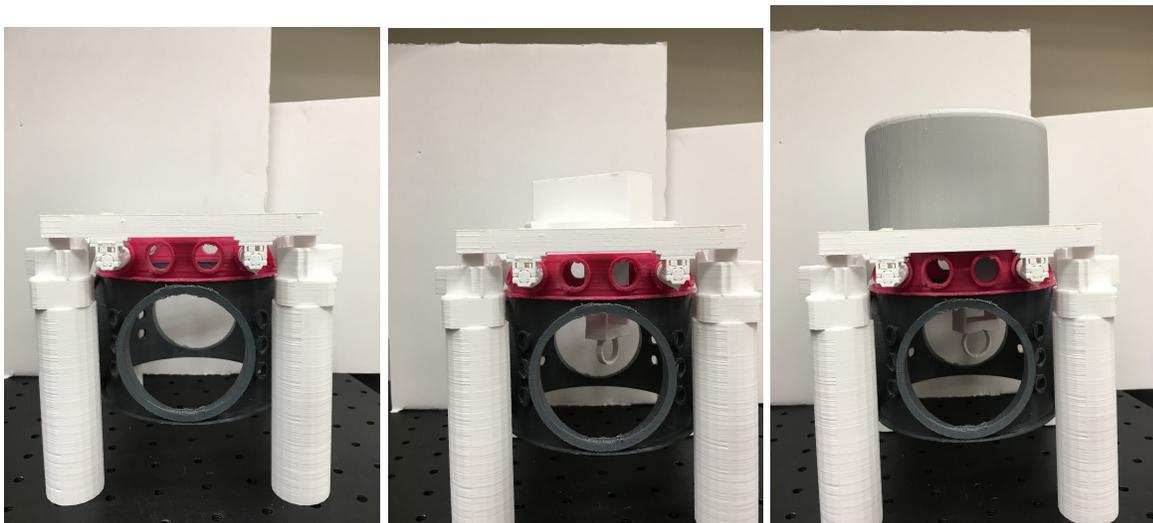
After you have finished printing all of the parts you can begin gluing items together. I have used 5-minute Epoxy as the glue of choice. It is strong and solidifies structures together. I have used the 5-minute Epoxy for larger parts such as the chambers, the HEPs, the A+ external support,

and the covers. Below I have included some pictures of my models and how I glued them for reference. Here I have also included a picture of the setup and me gluing a piece of the model together.



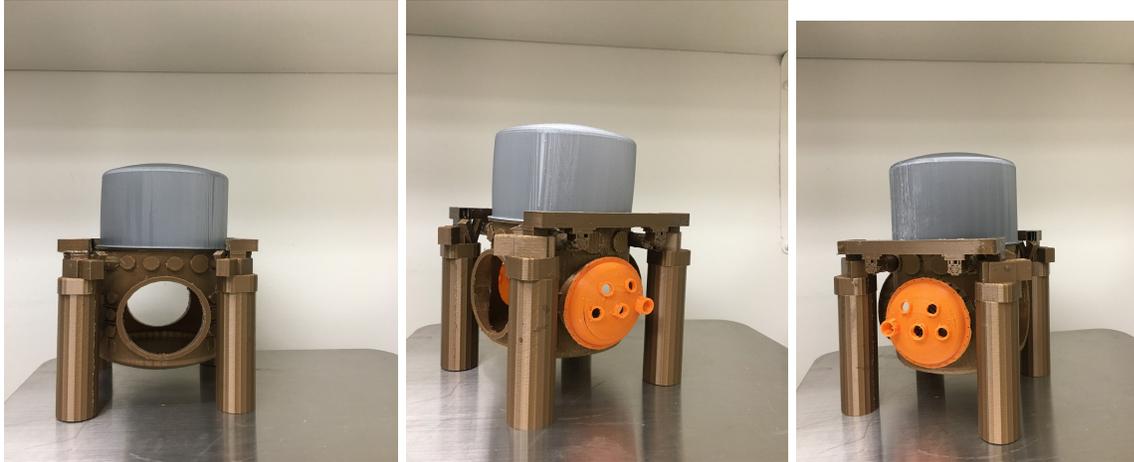
4.2.1 BSC

For the original model:



Here I have three pictures which represent the BSC Lower Shell Middle, Lower Shell Top, and the HEPI all glued and connected. In the second picture I have added the Quad Suspension for BS (or XY). The Quad Suspension does not need to be glued for the purpose of our hands-on model. Finally, in the last picture I have added the Top Hat which also does not need to be glued so one can look inside of the chamber by removing the hat.

For the A+ extension:

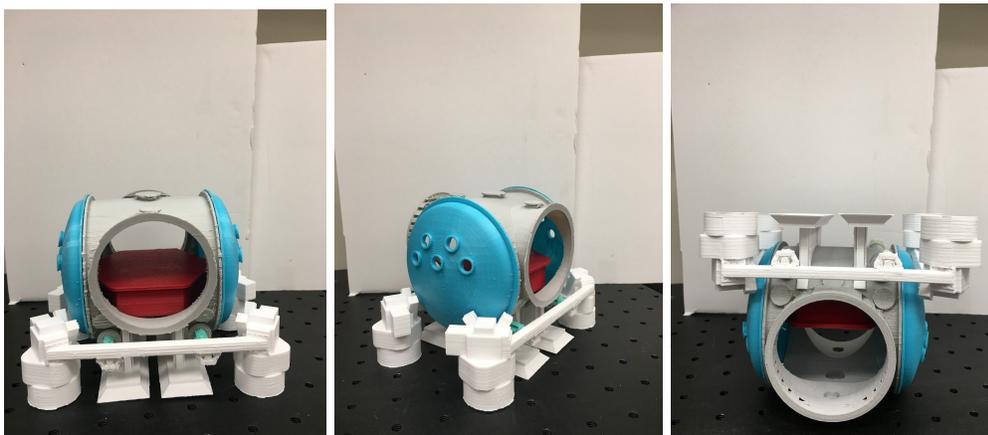


This assembly is for the BSC3 Chamber

Here I have a picture which includes the BSC Chamber and HEPI glued and connected together. The A+ extension does not have any BS or XY Quad Suspensions. Glue the two BSC3 Doors (Type 1 and Type 2) as shown above.

4.2.2 HAM

For the original model:

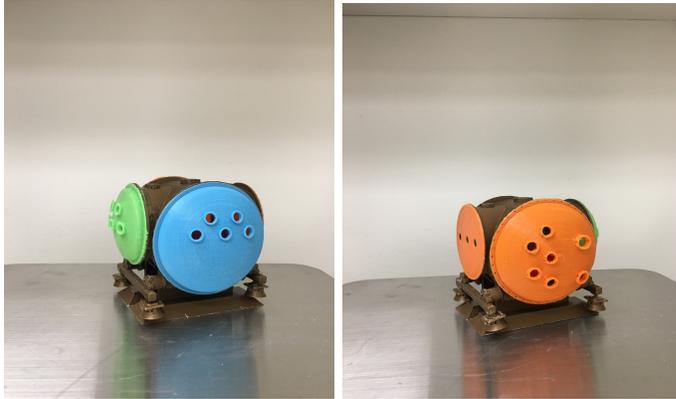


These pictures are a visual reference for the HAM Chamber and how it must be glued. All parts of this structure must be glued together. I have provided different views to show where each part is glued. (The updated HAM Chamber includes legs to avoid having to print and glue separate legs.) First you should insert the two ISI tables (top and bottom) with both flat ends facing up. Attach the two pieces according to their name, the bottom plate goes on the bottom which is then attached to the top plate. Insert these two ISI plates through the larger holes of the chamber with the rounded bottom plate facing downwards. Then glue the ISI plates in place.

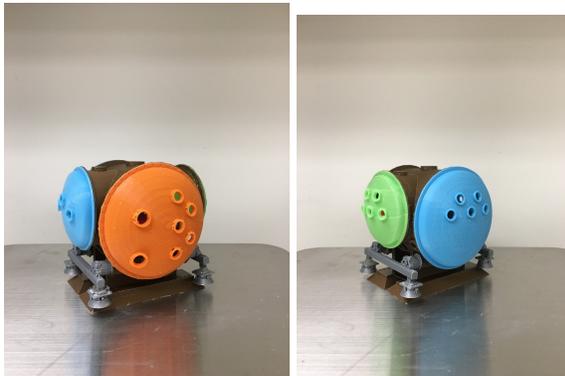
The 84 in covers then are glued onto the larger holes of the chamber. Finally glue the HEPI to the beams protruding from the bottom of the HAM Chamber.

For the A+ model:

The assembly of the HAM Chambers for the A+ model is very similar. However, instead of gluing the HEPI to the HAM Chamber, you will glue the A+ external support.



The pictures above correspond to the assembly of the HAM7 Chamber
The large blue cover is the HAM 84in cover, the small green cover is an original BSC Cover.
The small, flat orange cover is a HAM Septum door and the large orange cover is the HAM7 Cover. Glue as shown above.



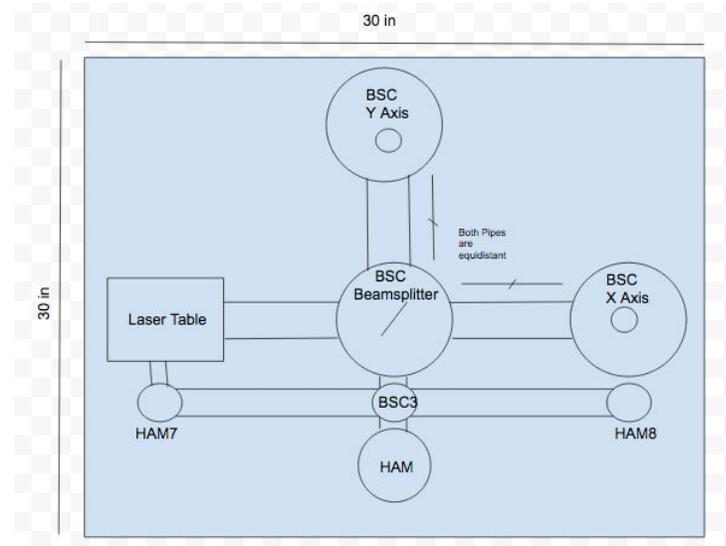
The pictures above correspond to the assembly of the HAM8 Chamber
The large blue cover is the HAM 84in cover, the small green cover is an original BSC Cover.
The small blue cover is a HAM 60in Cover and the large orange cover is the HAM8 Cover. Glue as shown above.

5 Breadboard Assembly

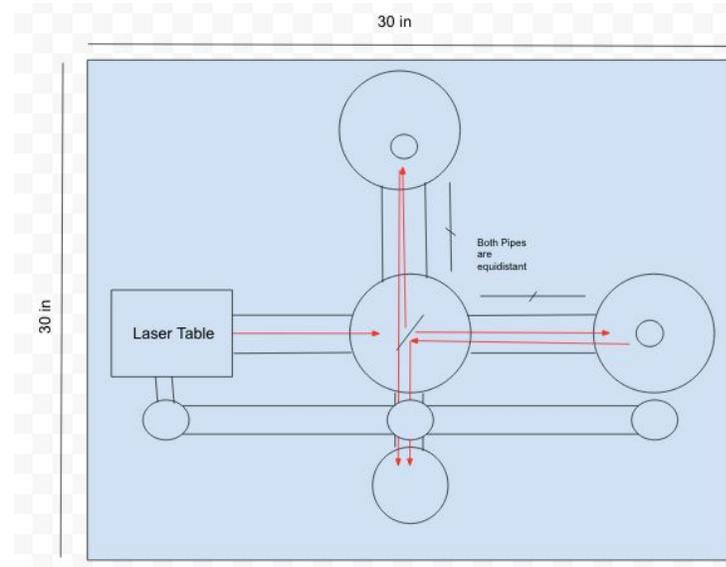
5.1 Basic Layout of the LIGO Mini Model

The layout below only generally indicates where each chamber and object lies. There are two different types of BSC Chambers. The BSC Chambers on the X and Y axis (the arms) contain

different Quad Suspensions with ISI. As you may have noticed there are two files named “BSC Quad.” One corresponds to both the X and Y arms and one corresponds to the Beam Splitter in the middle.



In order for the interferometer to work, you must make sure of several things when constructing it. It is important to have the X and Y arms equidistant from the beam splitter to ensure success. If one arm is further from the beam splitter, light will not appear at the end of the telescope (HAM chamber). The separate “arm” that runs alongside the x axis of the interferometer is called A+. A+ is a recent addition that contains two HAM Chambers and one BSC Chamber. Below I have highlighted the path the laser takes for the interferometer to work. Chamber labels have been excluded, so refer to the diagram above.

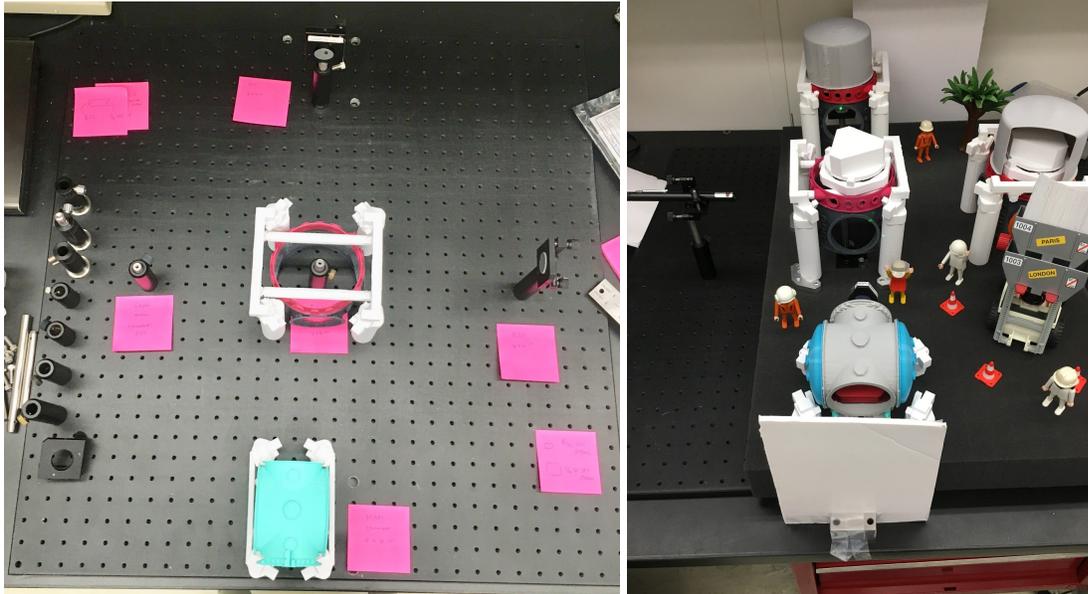


First the laser beam exits the laser table and arrives at the beam splitter. The beam splitter then splits the laser beam so that now there are two beams: one going straight towards the X axis mirror and one going perpendicular, towards the Y axis mirror. Both the X and Y mirrors then

reflect the light back towards the beam splitter. And once again, the beam splitter splits the beams so that the Y axis beam passes straight through the beam splitter towards the HAM Chamber and the X axis beam is split perpendicularly towards the HAM Chamber as well. Both beams (by both we mean the laser beam that has been split by the beam splitter) should end at the HAM Chamber. If they have traveled the same distance from the beam splitter to the corresponding mirror, back to the beam splitter, and finally to the HAM Chamber, then there should be a beam that appears on the card in the HAM Chamber. If no light appears, it signifies that one beam traveled further through the arms than the other.

5.2 Breadboard Parts

For my model, I used parts from Thorlabs that we already had in the lab. From Thorlabs I used Post Holders, Optical Posts, Optic and Mirror Mounts, a standard 30 x 30in Breadboard (with $\frac{1}{4}$ " holes 1" apart), a single-axis translation stage, and a green coated Beam Splitter. I also purchased a green laser pointer that is $<5\text{mW}$. It is important to have a laser pointer that is $<5\text{mW}$ to ensure safety. I used a green laser pointer because the Beam Splitter was coated for green light. It has an on/off button that remains on and off until you press the button. This is an important part of the laser because we want the laser to remain on during the entire presentation. Below I have included a picture of our actual Michelson interferometer setup. You may notice however that we do not have the single axis translation stage or the final lens at the HAM Chamber end. We did not add those in until we realized the fringes could not work with the original setup.



Above (on the right) is the picture of our final setup of the Michelson Interferometer with all of the chambers. Note the beam splitter and the mirrors are hidden by the chambers.

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Below I have included pictures of the A+ model fully assembled with a pvc pipe running through the three chambers. On the left is the HAM7 Chamber which sits right next to the laser table, in the middle is the BSC3 Chamber which sits next to the BSC Beamsplitter, and on the right is the HAM8 Chamber which sits next to the x axis BSC Chamber.

