Wrinkleless Mylar Shell Prototype for BONuS detector: Design and Procedure

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by

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Wrinkleless Mylar Cylinders: Design and Prototyping for the BONuS detector at Jefferson Lab

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Abstract

The second BONuS (Barely Off-Shell Nucleon Structure) experiment seeks to expand the detection range of the neutron structure to Bjorken x up to 0.8. For that, a new radial time projection chamber needs to be built, which is twice as long as the original one. The goal of this work is to make prototypes for the conducting mylar shell that generates a uniform radial electric field for the chamber, and to develop a specially designed apparatus and procedure that will reduce the wrinkles in this ultra-thin cylindrical mylar shell.

1 Introduction

In Quantum Chromodynamics, up (u) and down (d) quarks are the primary constituents of the nucleon, and they determine its quantum numbers. Consequently, the momentum distributions of the up and down quarks, u(x) and d(x), are of high interest. Here, x is the fraction of total nucleon momentum carried by one quark. One way to shed light on their nature is to measure the structure functions of the proton, F_1^p and neutron, F_1^n, since protons and neutrons contain both 3 valence quarks. Experiments have been run at Jefferson Lab measuring the ratio F_1^p / F_1^n in the lower range of x, which produced valuable data using a radial time projection chamber (RTPC). We want to determine the momentum distribution of quarks in the valence region (at higher x). Therefore we want to expand the detection range in order to observe the behaviour as the momentum transfer x goes to 1. However, the current luminosity possible with the existing RTPC isn't large enough to provide a high enough event rate. To increase the luminosity, we need to build a new RTPC, twice as long as the first one.

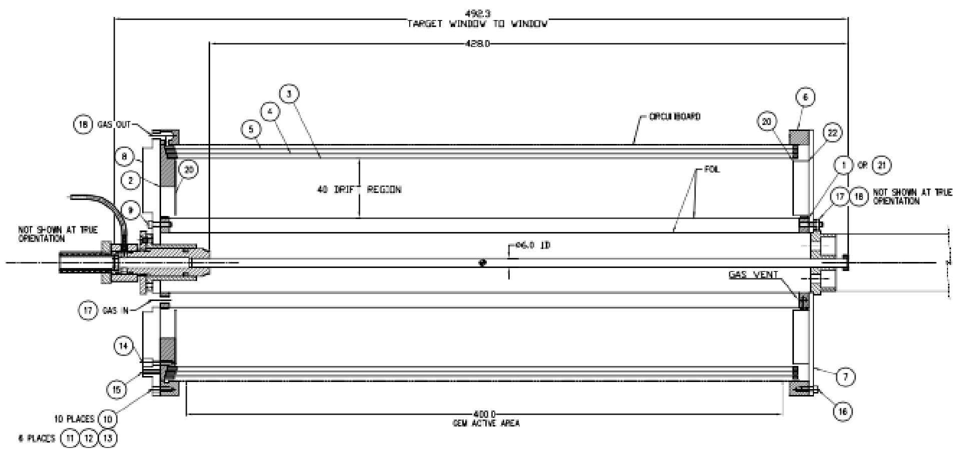

Figure 1: Preliminary engineering drawing of the new RTPC detector.

This specialised detector can detect low energy recoiling spectator protons liberated when an electron scatters from the neutron in a deuterium target. The RTPC consists of a cylindrical chamber with a Kapton straw in the middle which contains the gaseous deuterium target gas. Aluminised mylar shells connected to electrodes generate a radial electric field that falls as the reciprocal of the radius. In the cavity between the shells is a gas mixture. The chamber is placed in an external magnetic field of about 5 Tesla. When electrons scatter from the neutron in the deuterium target, the spectator proton will be liberated and bend in a curved path because of the external magnetic field. This curvature has to be measured by the ionisation trail it leaves in the gas. To collect the charge in this trail, we apply electric fields to the chamber using the aluminium mylar shell, so that all ionized electrons drift to the outermost shell of the chamber. The outermost shell is made of three layers of Gas Electron Multiplier (GEM) foils that multiply the ionization, creating a large enough electrical signal to be amplified using electronics. Each GEM foil has a multiplicative factor on the order of 100. These signals are digitalised and stored using the data acquisition system. Knowing the time that signals arrive at the GEM pad and their driftingvelocity, we can mathematically reconstruct the curve in the chamber and calculate its momentum. For an engineering drawing of the new RTPC detector, please see Figure 1. A picture of RTPC's cross section showing different layers of construction is given in Figure 2.

One problem of the old RTPC was the wrinkle problem. The aluminised mylar used to construct the cathode shells is only 5μm thick. It is designed to be thin because protons energy lost in the foils limits the momenta of slow protons that can be detected. Consequentially the mylar is too thin to be self-sustaining. For a comparison of a 100μm self-sustaining mylar shell and a 5μm shell, please see Figure 3.

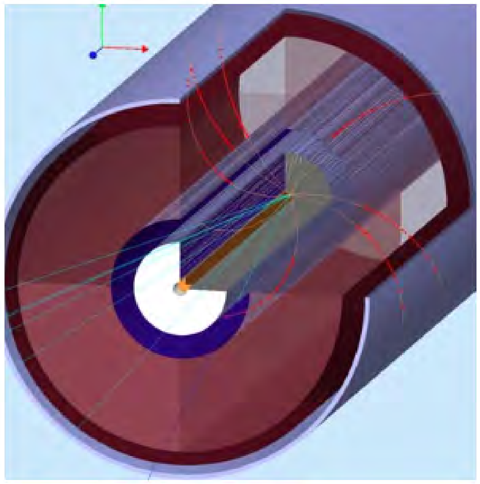

Figure 2: A picture of RTPC cross section. A kapton straw contains gaseous deuterium target (orange). A buffer gas fills the white volume that is surrounded by a ground mylar foil. The inner blue layer is the cathode, also made of mylar. Between the cathode and the next three nested layers of GEM foils(brown) is the drift region filled with specific gas mixture. The outermost cylinder are the readout pads.

To make and transport a cylindrical shell, we have to provide appropriate tensions on both ends of the mylar to stabilise its shape. Since uniformity of tension is very hard to produce, given the complex mechanical procedures involved in manufacturing the shell (like applying glue and attaching fixation rings), the mylar shell easily wrinkles and saggs. For a picture of the wrinkled cylindrical mylar from the old BONuS detector, please see Figure 4.

When the mylar shells are wrinkled, they no longer provide a uniformly radial electric field, and consequently distort the simulation and tracking results. My goal therefore is to design, prototype and build an apparatus to make cylindrical mylar electrodes without wrinkles.

2 Prototyping for the mylar shell

My goal is to make wrinkleless cylindrical mylar shells with 40mm length and 30mm radius. Given that the aluminised mylar is only 5μm, I started by testing the thicker mylars: 100μm and 20μm. If we cannot design an apparatus that can make wrinkleless cylindrical shells using thicker mylar, it is unlikely that we can make 5μm wrinkleless cylindrical mylar shells. Therefore I adopted an amelioration methodology: to design an apparatus that can make wrinkleless cylindrical shells out of self-sustaining mylar (20μm and 100μm) and then to improve the performance of apparatus and procedure when applying it to 5μm mylar, the not self-sustaining one.

Figure 3: Mylar cylinders of 5μm and 100μm. The top shell is made from 5μm mylar. As we can tell, the shape is not self-sustaining. Tension has to be applied at the fixation rings on both ends to stretch the mylar into cylindrical shape. The bottom shell is made from 100μm mylar. It is self-supporting, but too thick to let slow protons go through.

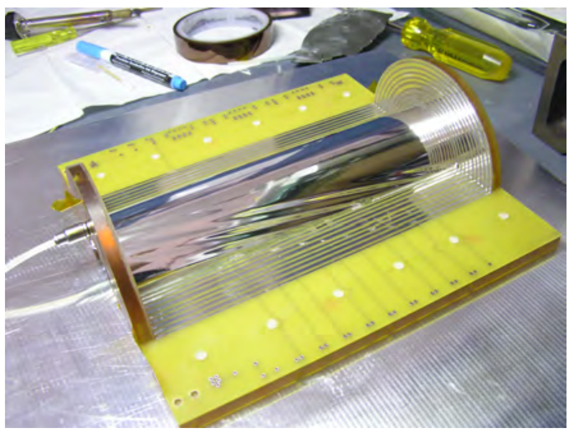

Figure 4: The wrinkled cylindrical mylar shell from the first generation BONuS detector.

In the next two sections Design and Procedure, I propose a prototype apparatus that successfully made two wrinkle-less cylindrical shells from 20μm and 100μm mylar (See Figure 5). Then in the sections Mylar sheet, Glue, and Rings, I will go into more details about how to manufacture individual parts of the 5μm cylindrical mylar shell and provide relevant parameters for each part. In the section Results I will showcase the best 5μm cylindrical shell we have been able to make in the lab and discuss where we could go from here. In the section Problems and Solutions, I will talk about problems that arise as we apply our apparatus design to the 5μm mylar and some solutions we have tried and evaluate how good they are. I will also discuss about possible alternative designs, like the wire model.

Figure 5: Wrinkleless cylindrical shells made by our designed apparatus. The left shell is made from 20μm mylar; the right shell is made from 100μm mylar. We can see that both shells are self-sustainable, unlike those made from the 5μm mylar (see Figure 4 for comparison)

2.1 Design

We came up with the basic elements of the apparatus by thinking through the process. We need a mold to give the initial cylindrical shape to the mylar sheet. It has to be removable after we have attached the rings to fix the shape on both ends of mylar shell. We need stable glue to attach the rings. We also need a set of rings, customised to the size of the mylar shell, to maintain the cylindrical shape at both ends even after we have removed the mold. Then we need to store the mylar shells until they are transported and installed as part of the actual RTPC.

Based on those needs, we designed the apparatus as shown in Figure 6. It consists of a base, four stands with caps, PVC pipe as the mold, and two fixation rings. All vertical stands can slide on the base and be secured at any position. They are all endented on the top to hold the PVC mold. Two of these are pictured in Figure 7. They have grooves in the middle to hold and fix the rings. The pipe is at least twice as long as the mylar shell to make sure that upon removal of the shell, the centre of mass of the mold remains

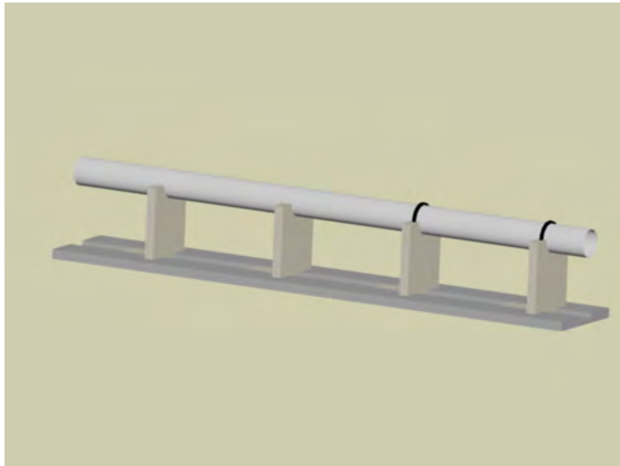

Figure 6: 3D conceptual drawing of the apparatus. The apparatus consists of a base, four adjustable vertical stands, two rings of fixation and a PVC pipe as the mold.

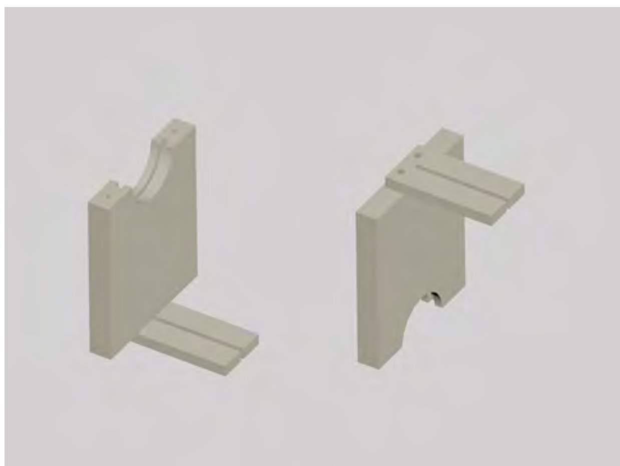

Figure 7: Adjustable vertical pieces with grooves in the middle to secure the rings.

within two vertical stands. Otherwise the mold cannot be removed horizontally without dipping and causing wrinkles on the mylar on its way out. Since in our case the mylar shell is 40cm long, we made the pipe 120cm long. Therefore it can slide out horizontally without removing the fixation rings or causing wrinkles on the mylar.

For the design details of the adjustable vertical stands, please see Figure 7; they all have grooves that can hold the fixation rings and the bottom part that allows them to slide on the base.

A picture of a fixation ring made from black acrylic board using a the laser cutter is shown in Figure 8. Details of how to manufacture the ring will be discussed later in the section 2.4.

Two special designs for the vertical stands are worth-mentioning. One detail is that we make the radius

Figure 8: Rings: cut from 1/4 inch acrylic board using a laser cutter.

of one side of the dented semi-circle of the stands slightly larger than the other(Figure 9: right). The purpose is to prevent the inner side semi-circle from touching and cutting the mylar. The outer radius of curvature is 30mm, which fits the radius of the pipe, so that the pipe can stay in place. The inner radius of curvature is 33mm to leave some extra space between the metal stands and the mylar. See Figure 9 (left) for the case when the fixation ring with the mylar is already in place. We see that there is some tolerance so the metal will not touch and cut the mylar.

Another design feature is that we make a corresponding cap for each stand as well. The idea is that the cap would help fix the ring in place and prevent it from wiggling. It could also provide some tension on the rings so that the mylar will be stretched a little bit to eliminate small wrinkles. The cap, as we can see from Figure 10, fits the stand with the same design of two different curvatures on each side, and a groove in between to fit the ring. We use screws to secure the cap on the stand.

For a view of what the real apparatus looks like in the lab, please see Figure 11. More pictures of the technical drawing of different pieces, and details of each piece can be found in Appendix A. The only caveat is that we made small adjustments in carrying out the technical designs as we tried to recycle existing materials to make the base and the stand.The real apparatus worked as expected in the design.

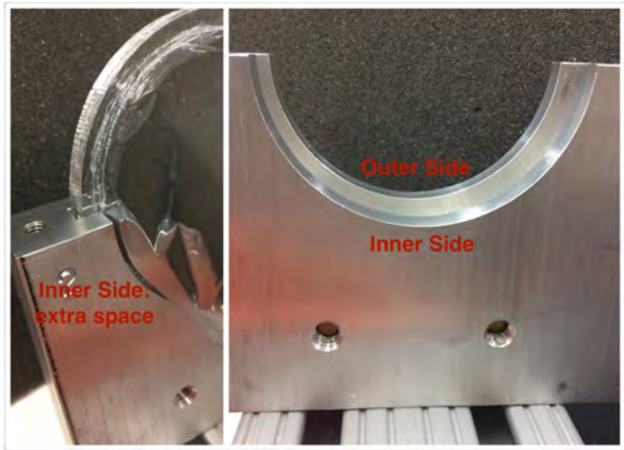

Figure 9: Special design detail 1. Two radii are slightly different to prevent one side of the stand from cutting the mylar.

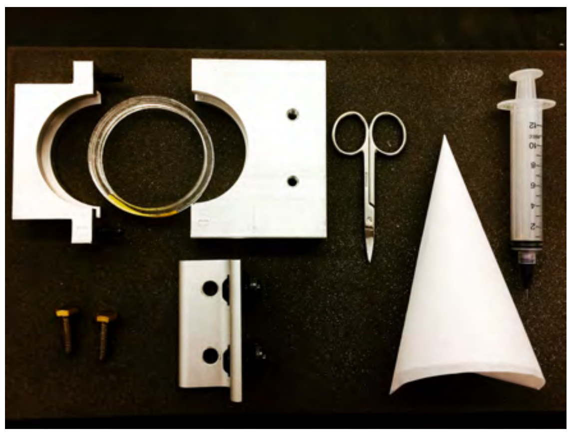

Figure 10: Special design detail 2. On the upper left corner is the cap. We make an accompanying cap for each stand to keep the fixation ring into place. We then use the screw on the bottom right corner to secure the cap onto the stand.

2.2 Procedure

First, we secure the vertical stands on the base and put the pipe on it. Vertical stands need to be evenly spread out, so that the pipe can be horizontally removed at the end of the procedure. The stands would prevent the pipe from rolling or slipping. Next, cut out the mylar sheet in a rectangle of appropriate size, with the top overlapping area of the cylinder less than 2mm. The size of the mylar sheet for a 30mm-radius cylinder should be around 193mm by 400mm.

We then wrap the mylar around the pipe and tape it on the top. The length of the base and the arrangement of the stands are calculated so that the mylar sheet can be wrapped between the first two stands. Then we lift up both ends of the pipe just enough to slide in the rings. Next we glue the rings to

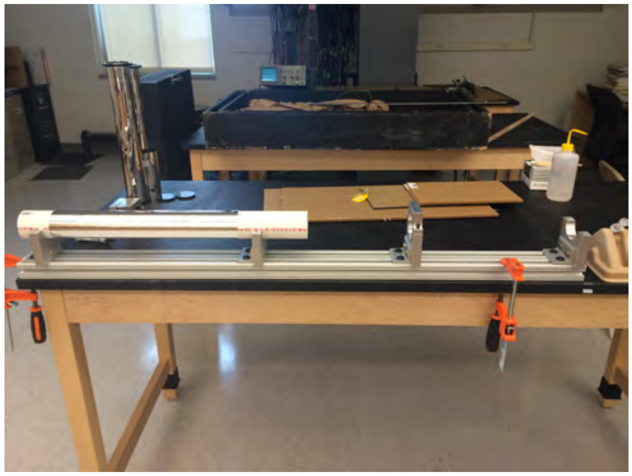

Figure 11: Apparatus setup in lab. In the formal procedure, the PVC pipe will be twice as longer as shown in this picture.

the mylar by putting the rings in place and letting the glue permeate through the tiny space between the ring and the mylar.

We let the glue cure for 24 hrs. Then we adjusted the stands to support to rings, put the caps on and gently slid the pipe out. We needed to do some small adjustments after the pipe mold was removed, until the remaining cylindrical shell has a minimum of wrinkles. See Figure 12 for a basic schematic diagram of the procedure and Appendix B for a complete series of diagrams of the procedure.

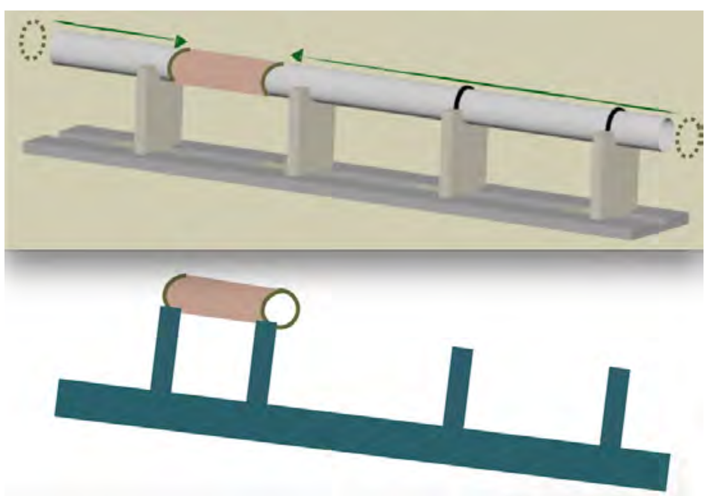

Figure 12: Schematic diagram of the procedure. Top part: slide in the rings. Botton part: gently remove the PVC pipe and secure the rings using clamps.

2.3 Mylar Sheet

Figure 13: Comparisons of connecting the edges using glue and tape. The top picture is using tape and the bottom is using glue. We can see that the glue occupies a larger volume and adds more weight to the mylar shell than the tape does.

We start with cutting out a 5 μm mylar sheet of the appropriate size 193 mm by 400 mm for a cylindrical shell of 30 mm radius and 400 mm length. Because the mylar is so thin, the best way to cut it in lab is by hand using a sharp, small scissors. We have also tested box cutters and art craft knives, both of which do not work well with the 5 um mylar because they easily cause zigzag cutting edges.

After choosing the best scissors, we used a small pencil to slightly draw cutting lines on the mylar sheet and carefully cut through using the scissors. Gloves must be wore at all time to prevent leaving fingerprints on the mylar sheet. After we finished cutting, we cleaned the PVC pipe and slowly wraped the mylar sheet around the pipe to see if the size fit. Then we taped the top edges of the mylar sheet together to make it a cylindrical shell.

Ideally we want to use two thin lines of single sided tape, one on the top and one on the bottom of the mylar sheet instead of glue. Glueing the top edges will cause two problems. First, we need the aluminised side of the edges of the mylar sheet to touch so that the whole shell is conductive; using non-conductive glue will create a non-conductive gap on the shell. Secondly, glue is much heavier than thin lines of tape. By glueing the top edges we are creating more gravitational force along the glueing line. Consequently, this line will sag due to the weight of the glue after we remove the PVC mold. See Figure 13 for comparisons of glue

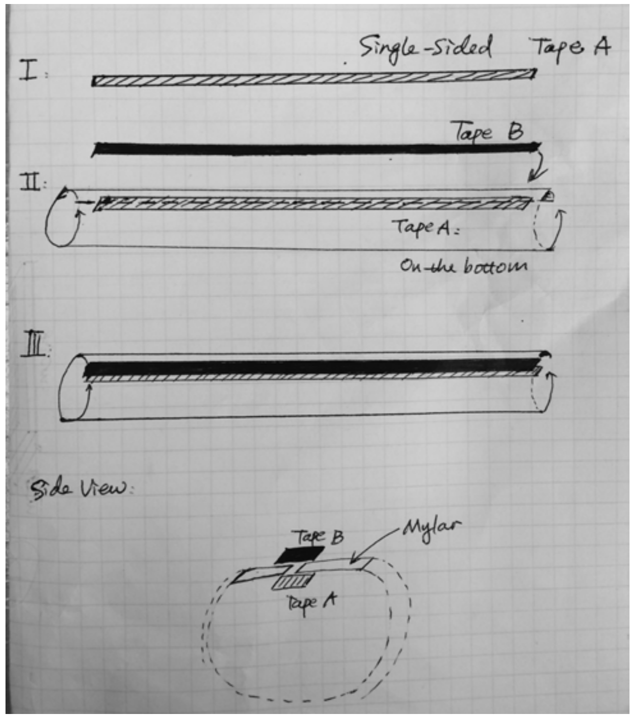

Figure 14: A schematic diagram showing how to apply two layers of tape to the mylar

and tape. See Figure 14 for a schematic diagram of how to tape the mylar.

2.4 Rings

We need to cut out a set of rings that could easily slide through the mylar shell on the PVC mold, yet tight enough so that when we finish applying glue between the rings and the mylar shell, the rings will not wiggle. We tested a group of rings with different inner diameters, the best of which are rings with inner diameter of 60.82mm and an outer diameter of 70.80mm.

To cut the rings, we use acrylic boards of 1/4 inch thickness. We want transparent acrylic boards instead of the black ones because transparent rings allow us to observe the glueing performance between the rings and the mylar when we wait for the glue to cure.

The laser cutter is a HL 40-5g Hobby Advanced Laser from Full Spectrum Laser. After creating the CAD file of our ring design (See Appendix C for CAD design and the interface of the Laser cutter software), we import the file into the Laser software (Full Spectrum Laser RetinaEngrave3D), and specify the cutting parameter: speed = 5, intensity = 100, repetition = 1, mode = vector cutting. When the rings are ready, we move on to the third stage: glue the rings to the mylar sheet.

Figure 15: Rings cut from 1/4 inch thick transparent acrylic board, using a laser cutter. Inner diameter 60.82 mm and outer diameter 70.80 mm.

2.5 Glue

Applying glue between the rings and the mylar is critical, since we want the force to be as uniform as possible. The first thing we want is a nice and consistent application of glue. Applying glues directly to the surface of the mylar does not work very well, as the glue line is too heavy and thick. We want a set of tools and techniques that could produce lines of glue thin enough to permeate through the small space between the rings and mylar without stacking badly on either side of the rings.

Figure 16: Syringe and the matching stainless needle for application of glue.

There are mainly two ways to achieve this. The first way is to use a syringe with a matching needle, like

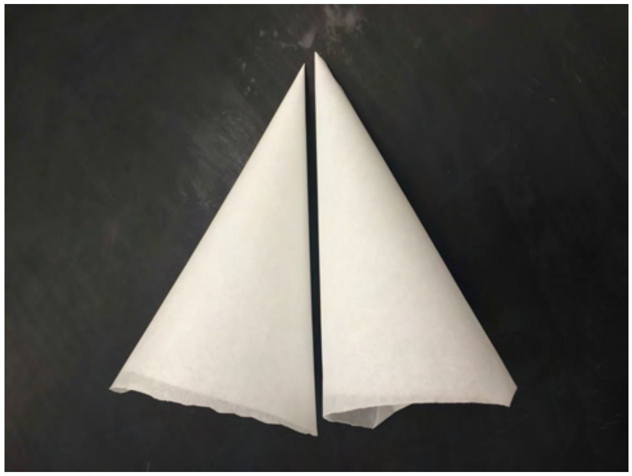

Figure 17: Mini pastry bags for the application of glue, made of parchment paper. Fill the bag with glue and cut a tiny hole on the tip. This is a cheap and effective alternative to the needle method.

the one in Figure 16.

When using syringe to apply the glue, we need to remember to use isopropanol to clean the syringe and needle first. Then we put the needle on and put the glue inside of the syringe. Before applying the glue to the rings, we hold the needle up and press the syringe to let out the air. We then test the glue on an extra piece of mylar to make sure it works well. Also we want to first think through everything that needs the application of glue, and apply the glue all at once quickly, since the glue will get easily dried and thus block the needle from functioning well. For this method, the needle has to be thrown away after each use and the syringe needs to be cleaned using water and isopropanol for reuse.

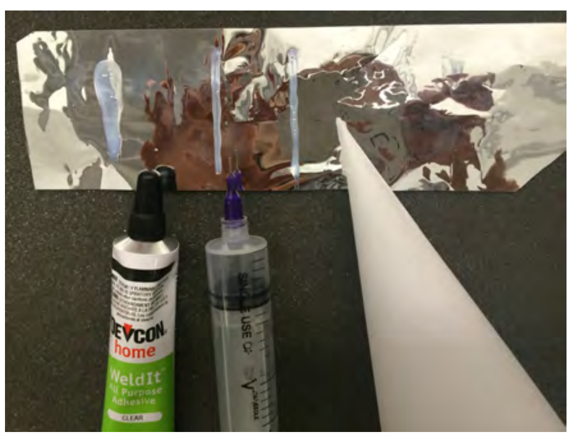

Figure 18: From left to right: Glue lines formed without a tool, with syringe, and with pastry bag. The latter two work much better than the first.

The second way is to apply some kitchen skills to make a mini pastry bag. We used an online tutorial from the Chef's Kitchen in making the pastry bag (Reference 2) and it works as equally well as the syringe while costing less. See Figure 17 for a sample of the mini paper pastry bag. From Figure 18, we can see that both methods work much better than directly applying the glue; between these two methods, pastry bag is the cheaper one and does not take a long time to make either.

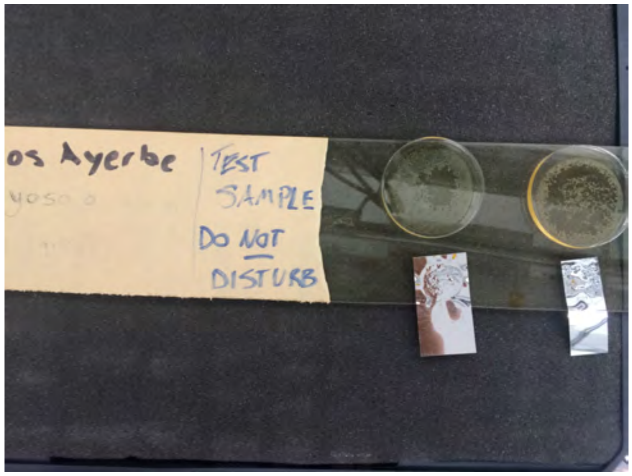

Figure 19: Test sample of glued mylar and acrylic board. The right disk is glued by our best lab glue Devcon WeldIt. As we can see , the glue sustains under the radiation of electron beams

Now that we have figured out the best way to apply glue, we want to make sure that the glue is stable enough. It cannot come apart over time or when undergoes radiation of the electronic beams. Therefore we tested different types of glue, and the type that works the best so far is the Devcon home WeldIt All Purpose Adhesive. It does not come apart over months, nor does itself cause any wrinkles on the mylar. The Devcon Weldit Cement has a composition of 30-60% (weight) of Acetone, 10-30% Methyl Ethyl Ketone (Butanone), and 1 -5 % Dybutyl Phthalate.

Carlos Ayerbe Gayoso sent glued samples of mylar and acrylic board into the test of electronic beams (See Figure 19) that will be used in the real RTPC. Two brands of glue, Duco Cement and Devcon Weldit Cement were tested. Both glues have similar working time and curing time, and similar viscosity as well. In the test, two transparent acrylic discs were glued to the acrylic board of same material using these two brands of glue. Two mylar pieces were also glued correspondingly to the acrylic board. As we can see from Figure 19, both glue performed well under the test: they did not come apart when exposed to radiation. However, Duco Cement failed the time test as it naturally came apart in the lab after a week or so, while the Devcon Cement continued to perform well over months.

Now that we know the glue is trust-worthy (though we might want to test more brands of glue in the

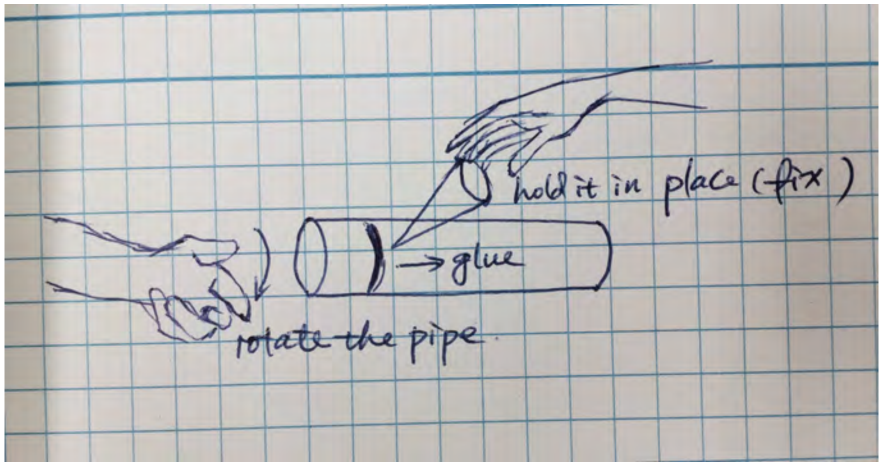

Figure 20: Schematic of a good procedure to improve the uniformity of glue

future), we set off to solve the uniformity problem. When applying the glue between the mylar and the fixation rings, we want the glue to be as uniform as possible. One trick is to fix the glueing point, and slowly rotate the PVC mold with mylar shell on it. See Figure 20 for an illustration. Ideally by mechanising this process, one can achieve a nice uniform line of glue.

Since we want the glue to permeate through the tiny space between the mylar and the rings, there inevitably will be some extra glue piled up on both sides of the rings . We don't want that situation to happen, because extra glue means extra weight and bad uniformity of tension, both of which can generate serious wrinkles.

One solution is to apply glue first on the mylar and push the rings outward so that the extra glue will be pushed to accumulate on the outer side of the rings. Then we use box cutter to cut off the extra mylar. A schematic diagram of the process is in Figure 21. Figure 22 is the comparison before cutting off the extra mylar and after. The extra mylar and glue have to be cut off because leaving it on will cause bad wrinkles, as the metal stands will touch the mylar on the outer side of the rings.

2.6 Results

During our process of making the 5 μm cylindrical mylar shell, many improvements of design have already been made throughout the way. All techniques that improve the quality of the shell are already fully included in the above sections of design, procedure, and manufacturing of individual pieces. Still many problems are left yet to be solved, like the problem of uniformity and that of non-vertical ring. Those problems and proposed solutions will be discussed in the next two sections.

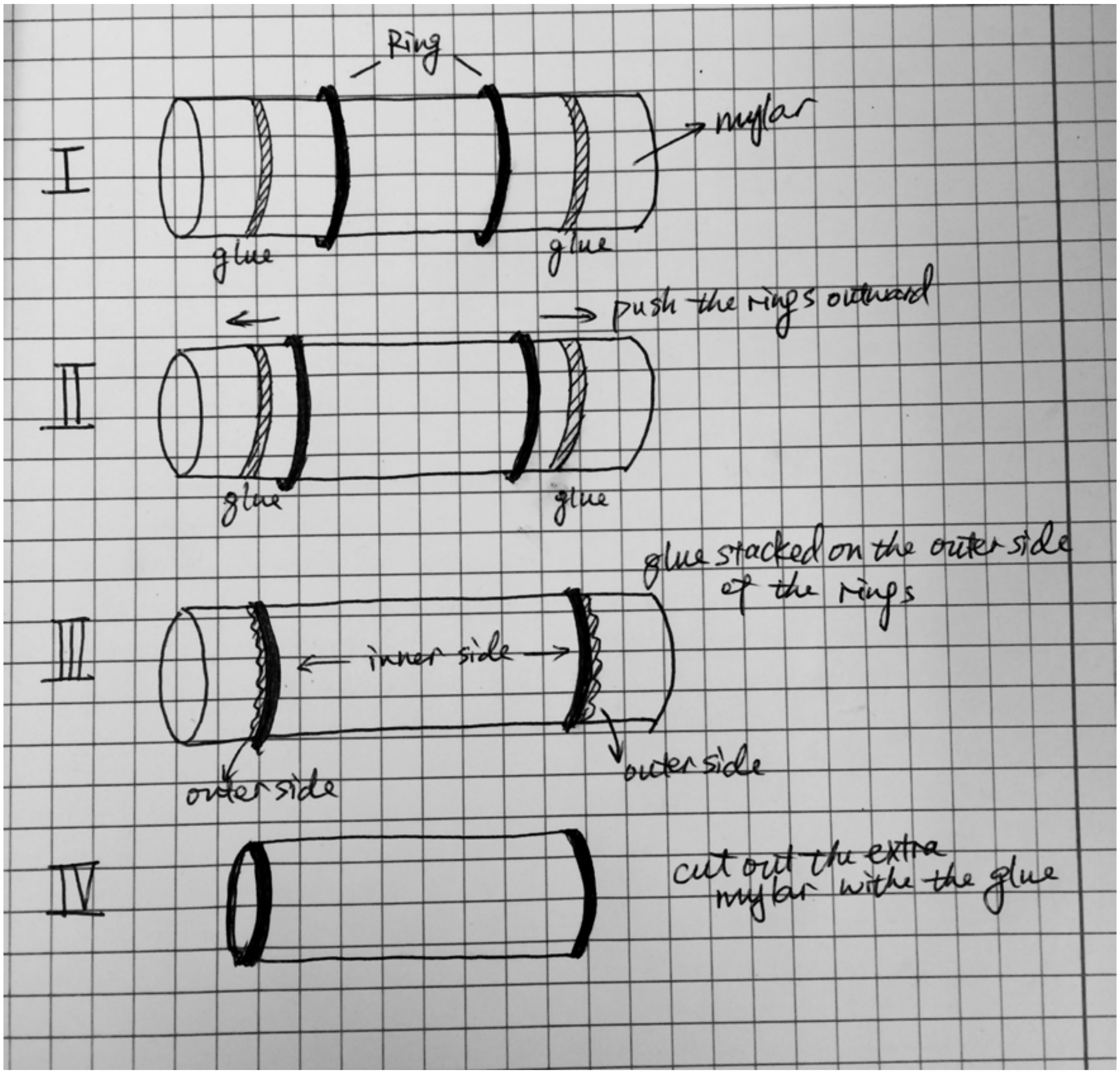

Figure 21: Schematic procedure for reducing the accumulation of glue on either side of the rings.

In this section, we showcase the best 5 μm cylindrical shell that we have ever made in this lab, and argue that it is possible to apply similar procedures to achieve our goal of wrinkleless mylar shell as long as we are careful to avoid problems. Figure 23 shows the best shell we have made in this lab. We call it a half-success, because the shell performs perfectly on one side without any serious wrinkle (detail in Appendix Figure 39), but horribly on the other side with bad wrinkles (detail on Figure 40).

Now this situation is exciting but also frustrating. The good wrinkleless side persuades us that it is indeed possible to use the horizontal model with fixation rings to create mylar shells without serious wrinkles. Now that we have successfully made it one side, the task is really to make it both sides and we will be done. Yet it is harder than we thought to replicate the success of Figure 39. We first did an analysis through

Figure 22: Extra mylar on the outer side of the ring (left). Extra mylar cut off by box cutter; ring fit in place of the groove (right).

comparison of both sides to see what were the differences that caused the drastically different performance of mylar. And we realised that it was once again just the problem of uniformity. The glue was more uniform on the good side than on the bad side. The difference in uniformity can be caused by several facts, including largely luck. Somehow the glue ended up better on the left side than on the right side, though we applied exactly the same procedure to both sides. But our goal is now clear: to improve on the procedure more to get higher chance of uniformity like in the case of left side rather than the right side. Aiming at this goal, we identify following problems that cause non-uniformity and propose some solutions to alleviate the problem.

2.7 Problems and Solutions

The problem of non-uniformity is sometimes caused by the mylar being not wrapped tightly enough, so that the fixation rings do not necessarily fit the mylar cylinder. To address this problem, we have tried several different ways. One way is to moisturise the mylar sheet so it could cling to the pipe. This turns out to be bad, because the mylar sheet would cling too tightly to the pipe for us to remove the pipe afterwards. Another solution is to use clamps on both ends of the mylar to hold it tightly in place. We have not yet tried this method.

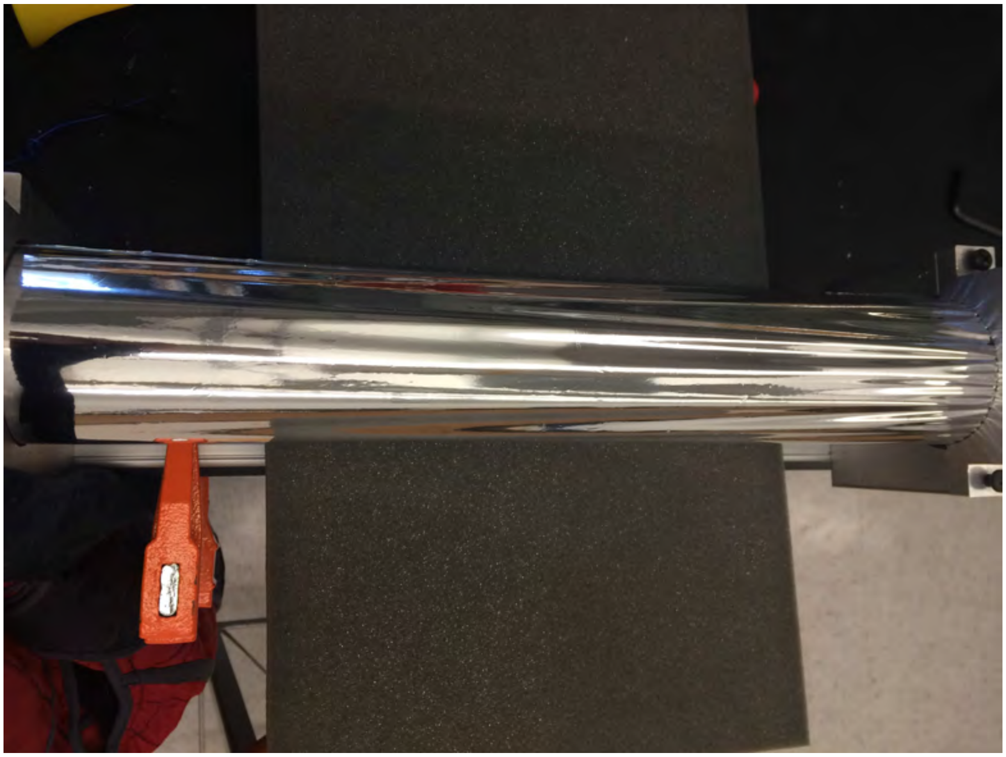

Figure 23: Best cylinder we have made from the lab. Perfect left side but horrible right side. We call it a half success.

The second problem of the non-uniformity is caused by the glue not seeping uniformly through the space between the mylar sheet and the rings. This is a hard one to solve because the glue situations in every individual case differ as we manually applied the glue. There are two possible solutions. One is to use superglue instead of glue, so that the tensions throughout the ring are all so strong that the difference of non-uniformity is marginal. We have not tried this method, yet we have to be cautious that if the tension is too strong it might break the mylar sheet, as such cases happened in the past when we applied too much glue to the mylar. Another solution is using an airbag to force the mylar sheet to be in uniform touch with the rings. Since the air will push the sheet towards the rings, the glue will hopefully be guaranteed to touch every single space between the ring and the mylar sheet. We are looking forward to try this technique.

The third problem of non-uniformity arises because the ring does not stand perfectly vertical inside the groove. It is because as we cut the rings using the laser cutter, the bottom layer of the acrylic board gets less heat and intensity, and therefore is slightly larger than the top layer (since less material is burnt away by the heat). To solve this problem, we need a better laser cutter. Our current laser cutter cannot perform at a better resolution capacity.

3 Conclusion

We have successfully shown that it is possible to make a 5 μm wrinkleless mylar shell, as we managed to manufacture a shell with its left side wrinkleless. We argue that the key is to make sure that the glue is applied uniformly to the ring and mylar, so that the tension provided by the glue is uniform. Where we can go from this point is to explore better ways, including possible procedures of mechanisation, to improve the uniformity of tension. For that purpose, some solutions have already been proposed in section 2.7. Alternative designs may also be proposed and compared to our model.

4 Reference

1. BONuS_MRI proposal (unpublished)

2. Chef's Kitchen: demonstration of pastry bag technique. *https://www.youtube.com/watch?v=pxxmYMntRQI*

3. *S.F. Biagi.* Monte Carlo Simulation of electron drift and diffusion in counting gases under the influence of electric and magnetic fields.

5 Acknowledgement

I would like to thank Professor Keith Griffioen and post-doctoral fellow Carlos Ayerbe Gayoso for their support, mentorships, and help. I also want to thank Will Henninger in the machine shop for carrying out our design, advising materials, and constructing the apparatus.

6 Appendix

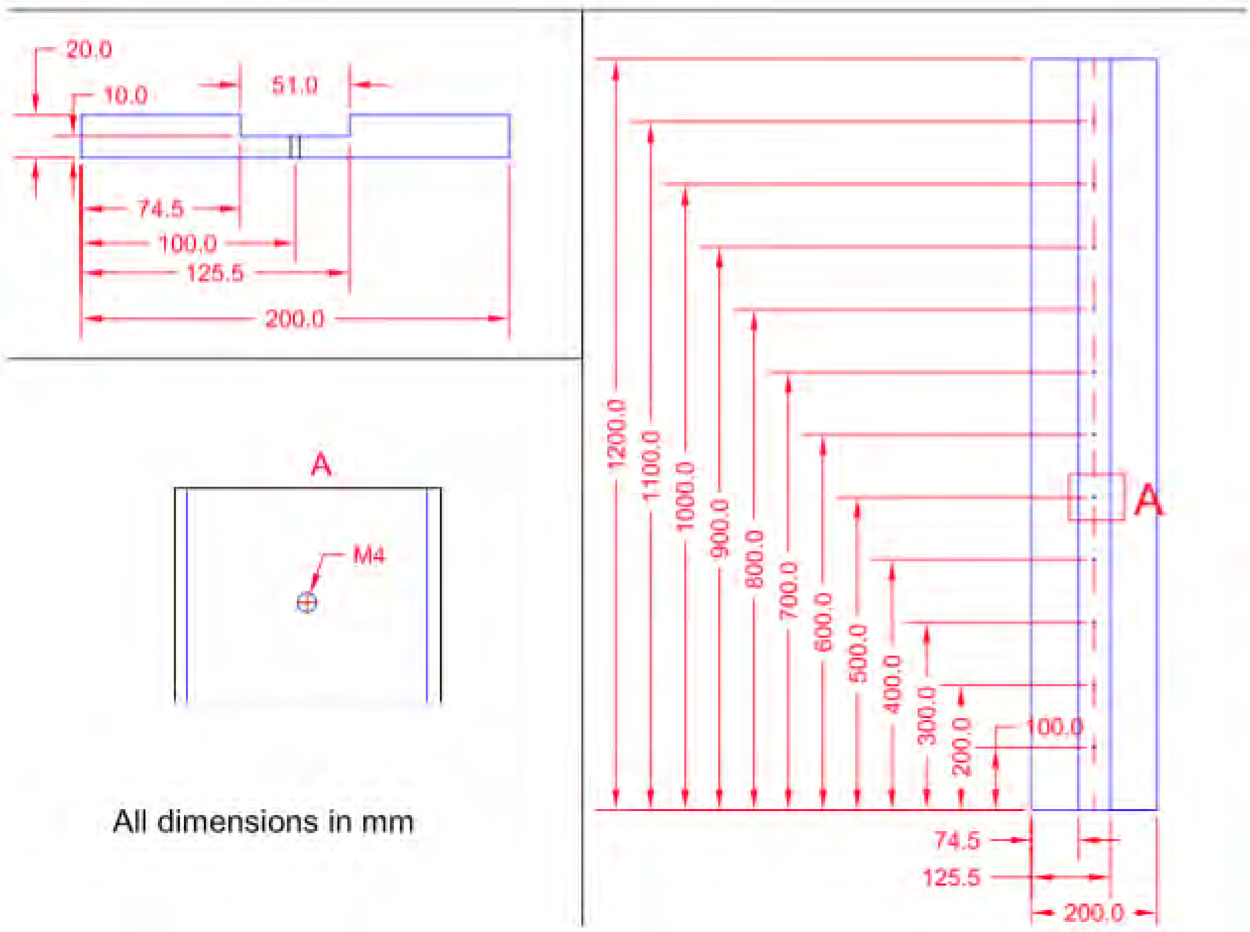

Figure 24: Construction apparatus: Technical drawing of the base.

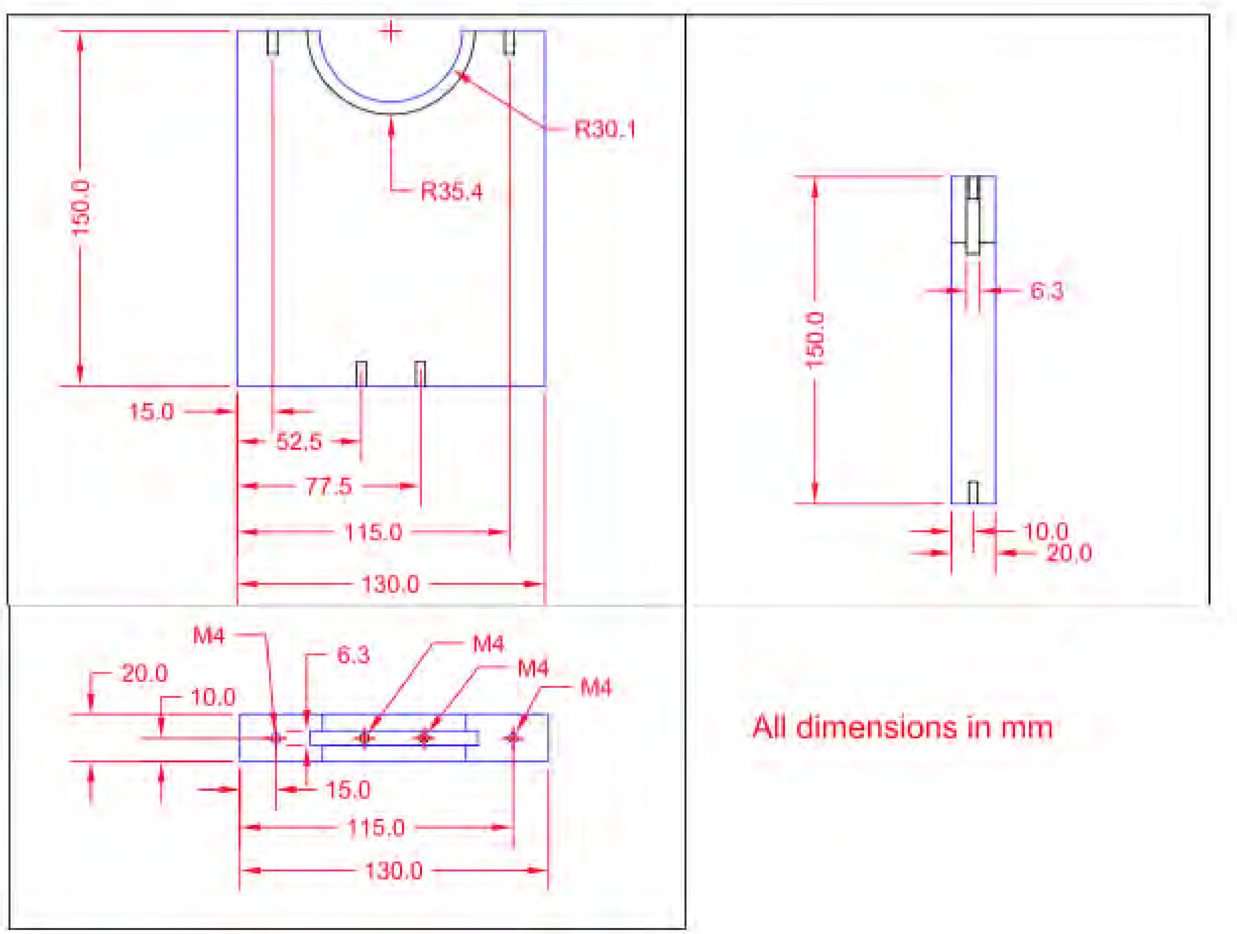

Figure 25: Construction apparatus: Technical drawing of the vertical piece

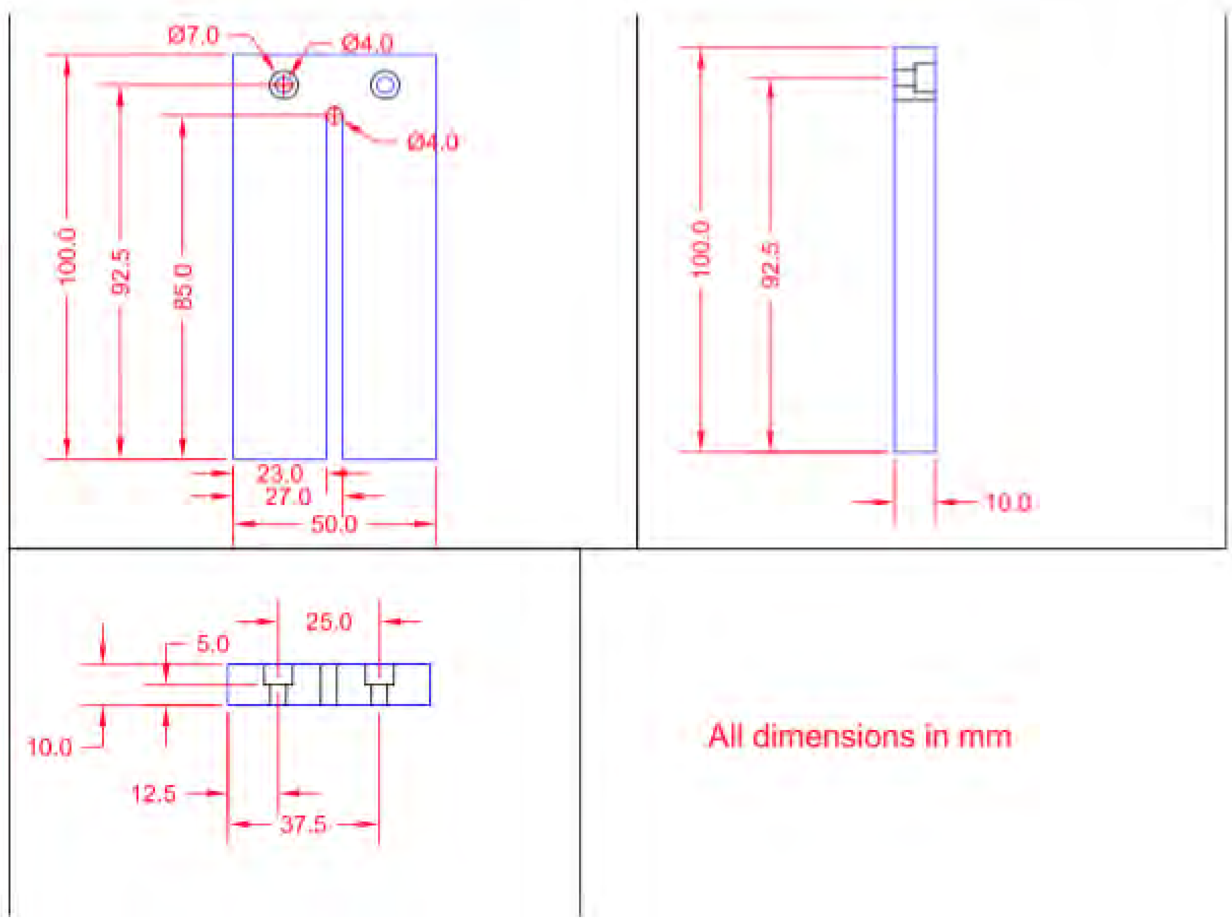

Figure 26: Construction apparatus: Technical drawing of the horizontal piece. It is attached to the vertical piece to allow it sliding on the base.

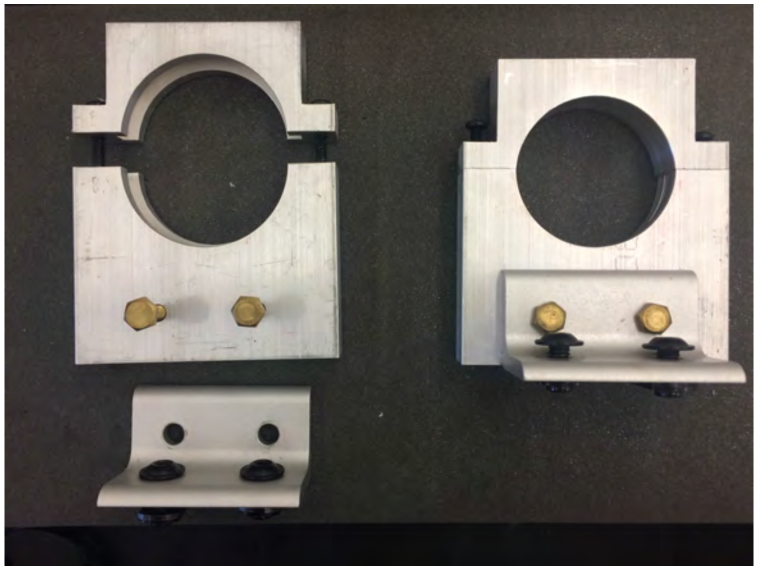

Figure 27: Vertical stands in lab: different components, including a cap, a vertical piece of stand and a horizontal piece to slide on the base.

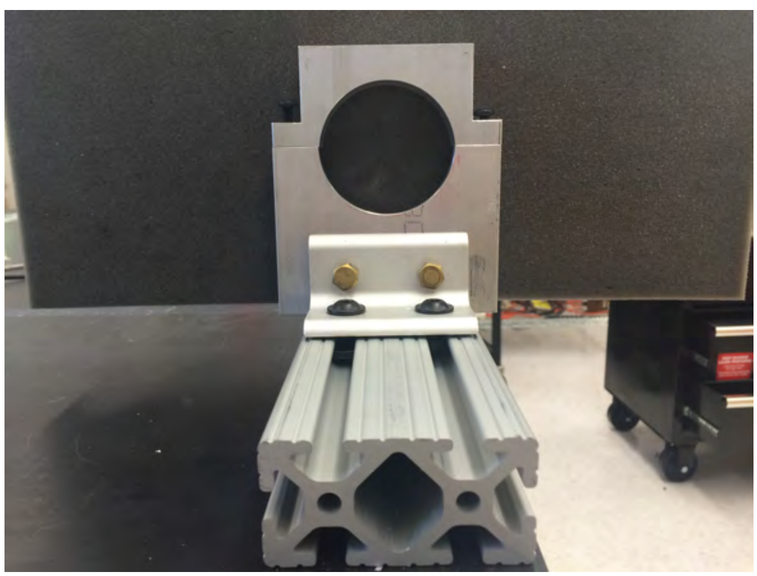

Figure 28: Vertical stands on the base, which are free to slide along the track, but can be clamped down in place.

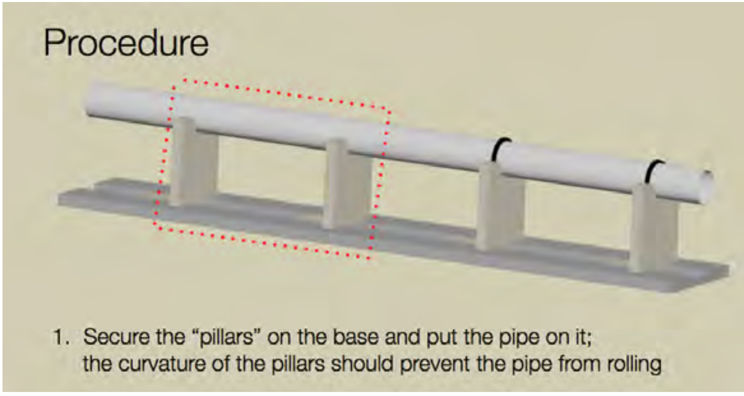

Figure 29: Procedure Step 1

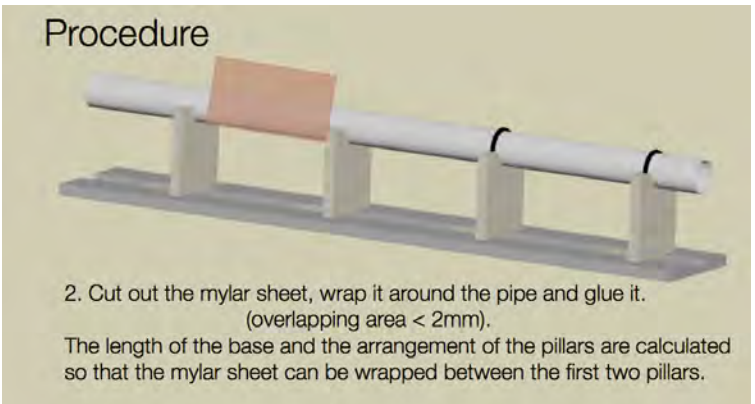

Figure 30: Procedure Step 2

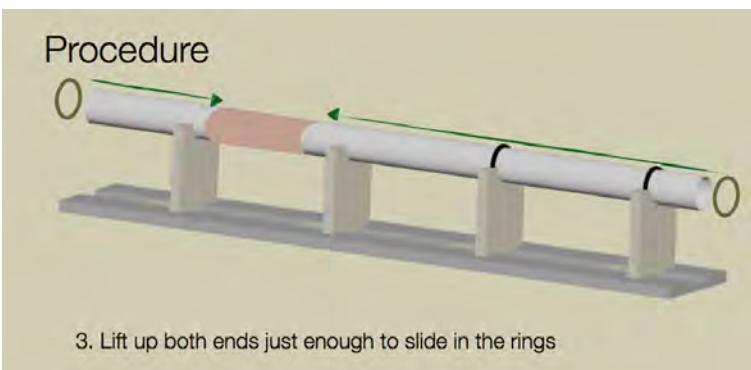

Figure 31: Procedure Step 3

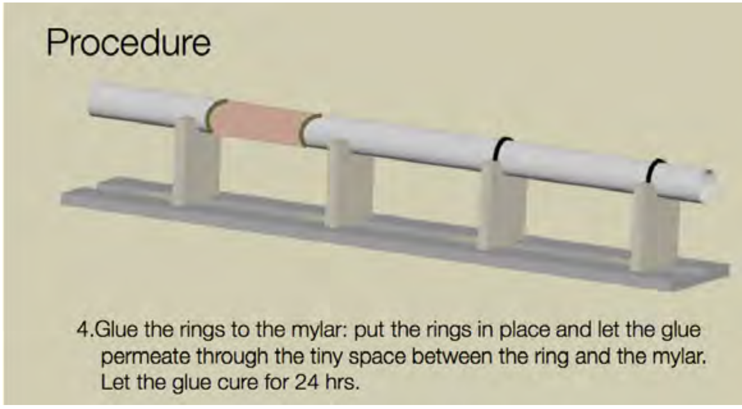

Figure 32: Procedure Step 4

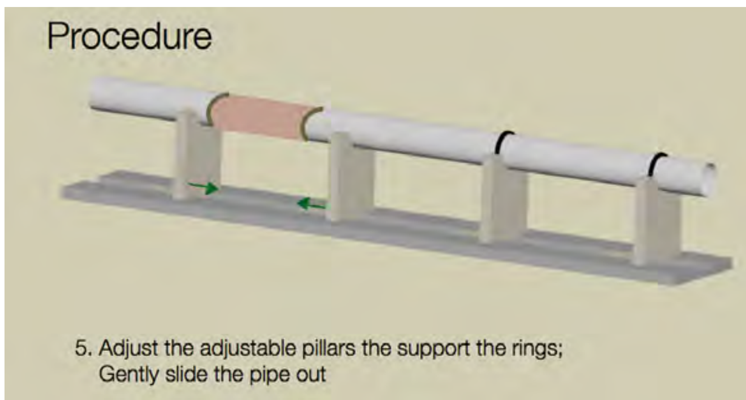

Figure 33: Procedure Step 5, part I

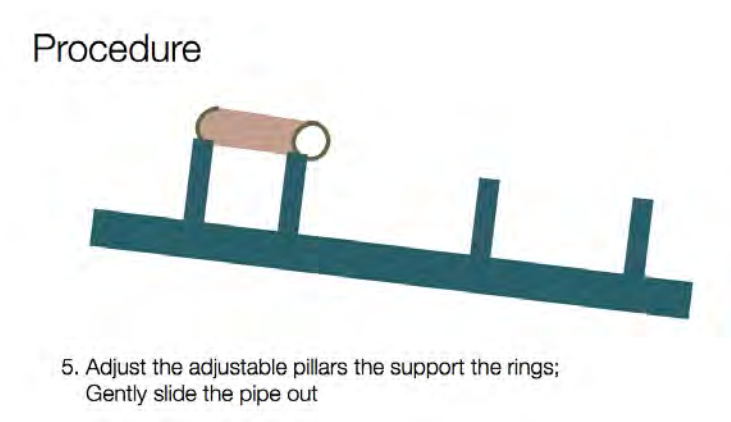

Figure 34: Procedure Step 5, Part II

Figure 35: Laser Cutter

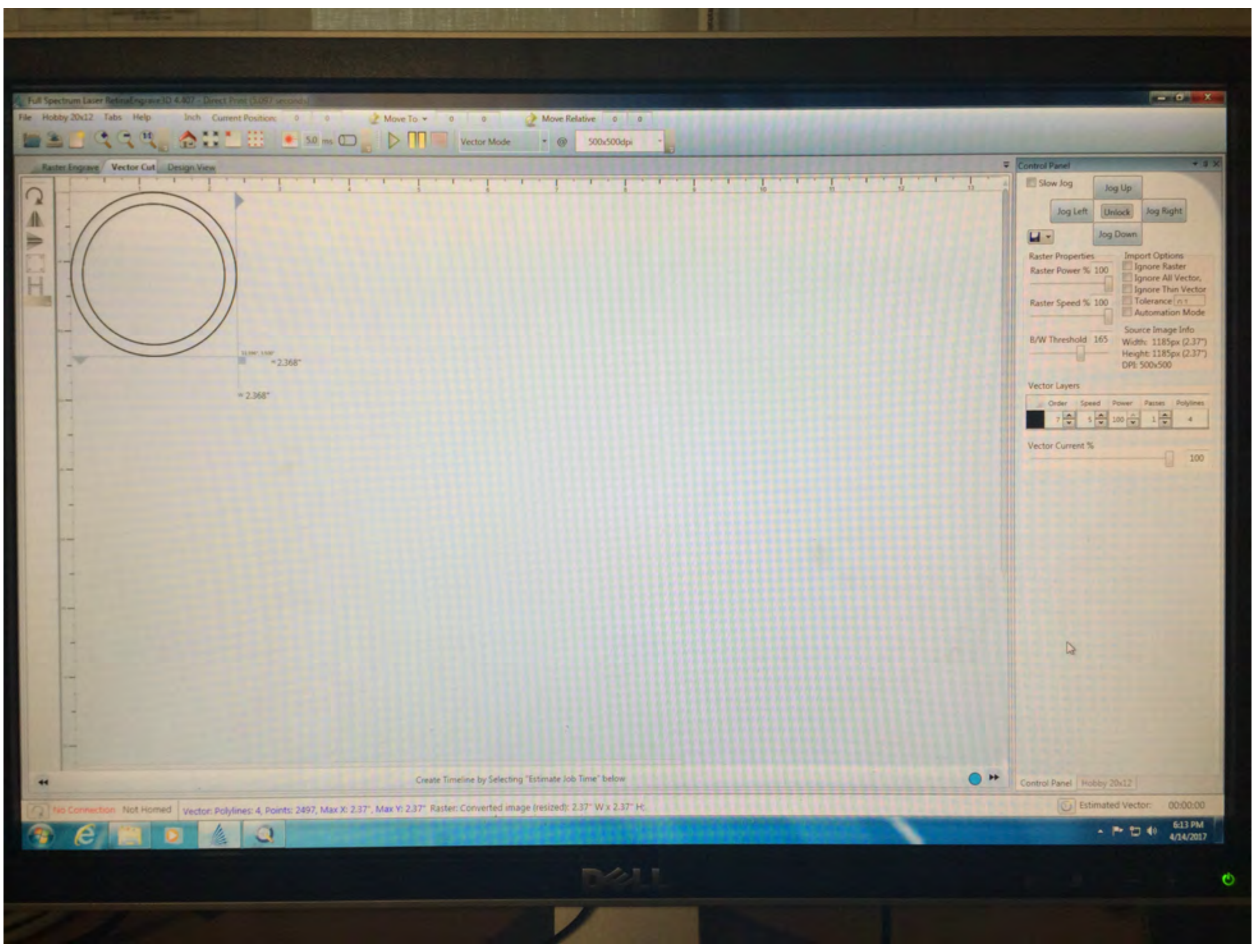

Figure 36: Laser Cutter Software Interface. Intensity =100, Speed = 5, Repetition = 1.

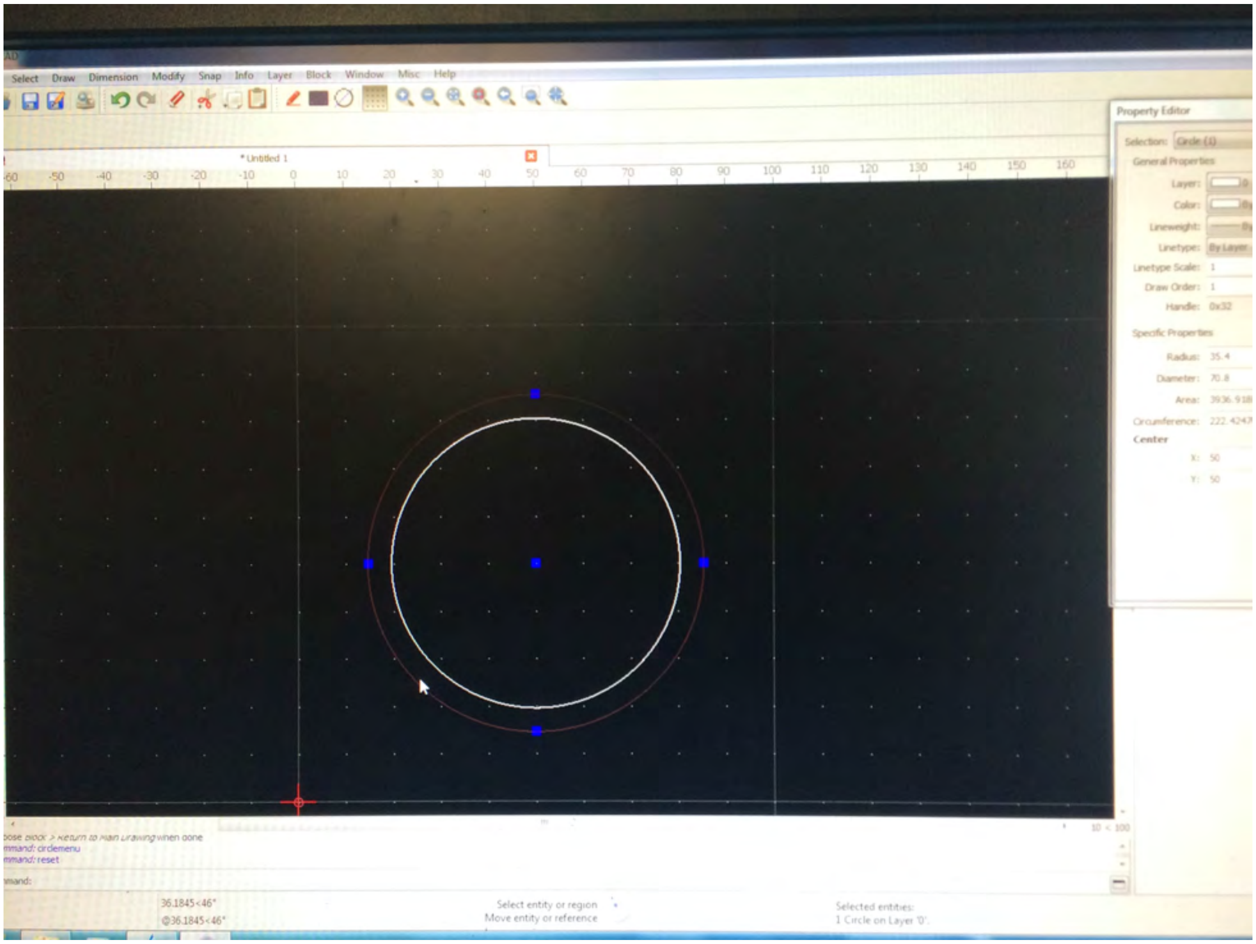

Figure 37: Ring design: CAD file

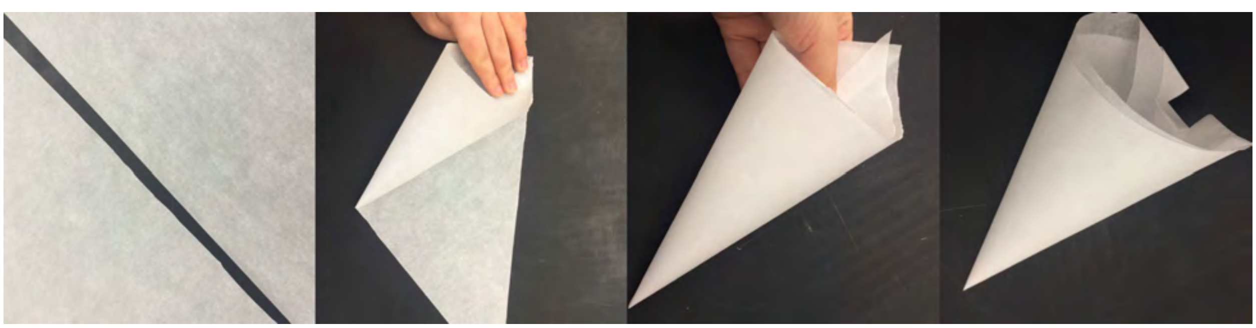

Figure 38: Glue Technique: pastry bag. Credit to A Chef's Kitchen online youtube video at *https://www.youtube.com/watch?v=pxxmYMntRQI*

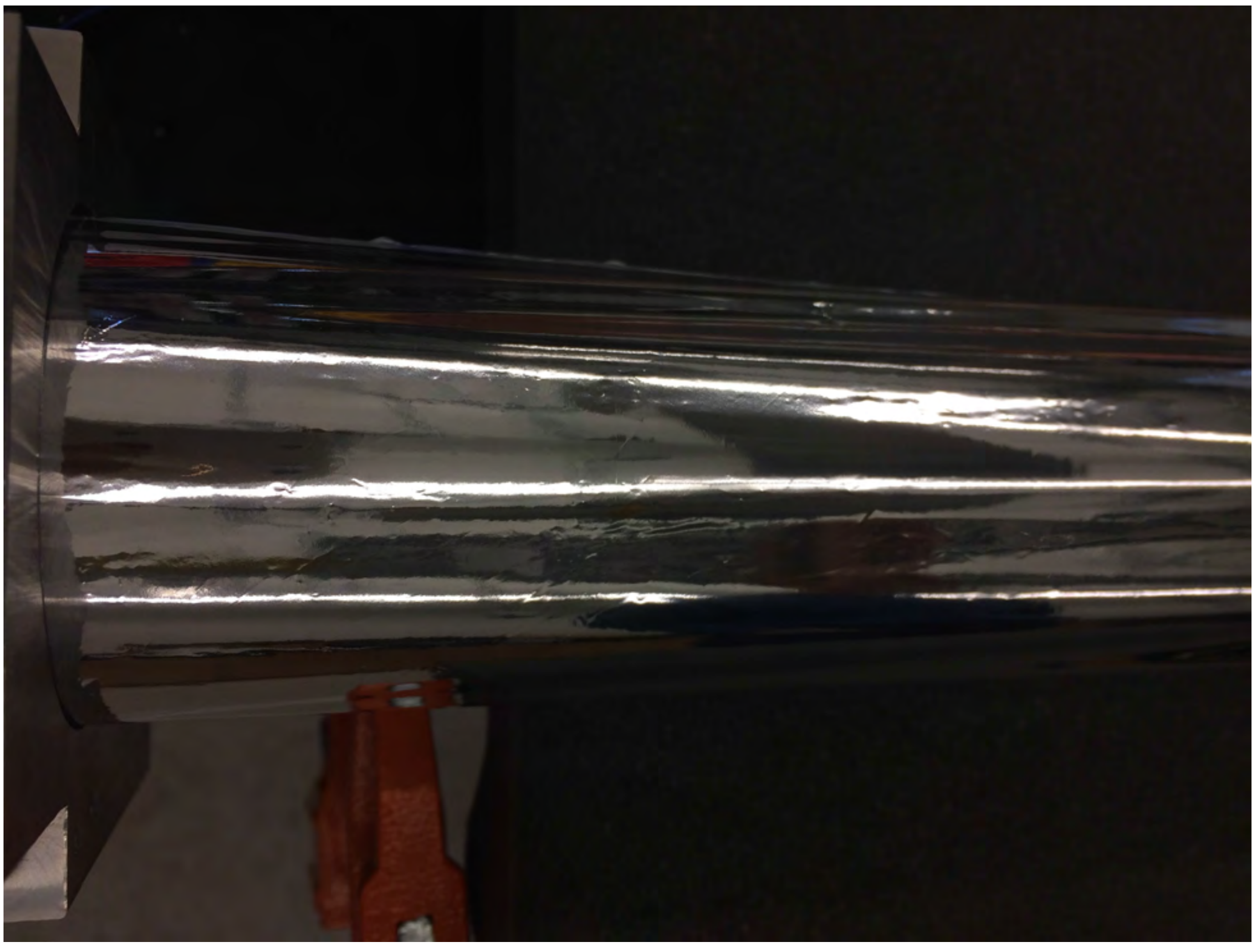

Figure 39: Good side of our result: the half success. No serious wrinkles due to tensions.

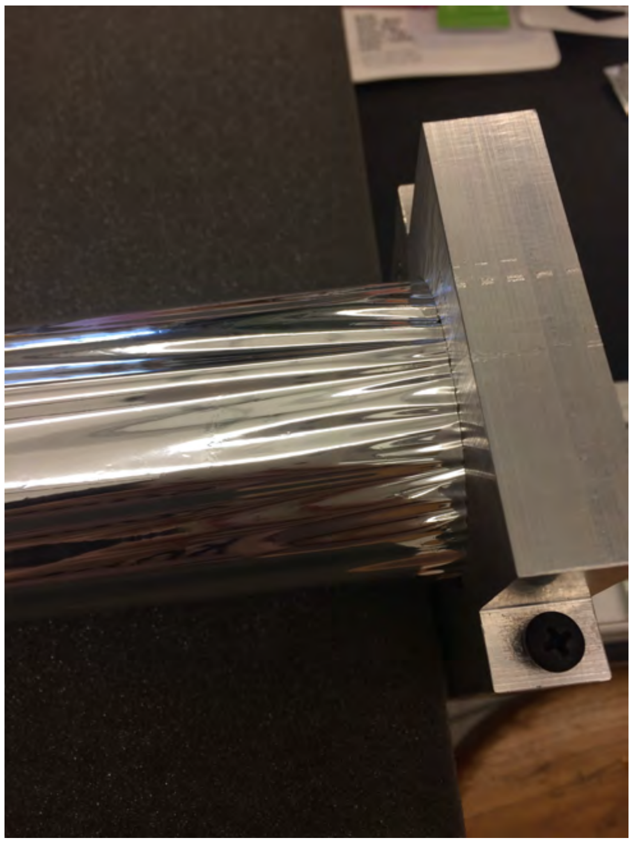

Figure 40: Bad side of our result: the half success. We can see bad wrinkles