Prototype Cryogenic Induction Motor for use in a Cosmic Microwave Background Polarimeter

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Abstract

I designed a three-phase induction motor to turn a half-wave plate to be used as a polarimeter. The motor contains 18 solenoids with sinusoidally changing magnetic moments on the stator and 6 permanent magnets on the rotor. The magnetic fields of the solenoids pull the magnets on the rotor causing the rotor to turn. The first design used a mechanical bearing to test the induction drive system at room temperature. This test showed the induction system worked and could turn the rotor smoothly with an angular frequency range of 1Hz to 5Hz. The second model was designed to operate at 5K and use a superconducting bearing to decrease friction. This model has yet to be tested at 5K.

1 Introduction

The cosmic microwave background (CMB), which originates 380,000 years after the big bang during the photon-decoupling epoch, is the oldest light in the universe. Up to this time, the universe was comprised of photons and a plasma of electrons and protons. Neutral particles could not form because of the high thermal energy. The high density of charged particles caused the mean free path of photons to be short due to Thomson scattering. As the universe expanded and cooled, the energy became low enough for neutral atoms to form. This drastically decreased the density of free charged particles and therefore increased the mean free path of photons, allowing them to propagate throughout the universe. These photons are the first photons that could propagate freely and the CMB is the signal generated by these photons.

The CMB radiation has an almost uniform temperature of 2.73K[1] with variations on the order of one part in ten thousand. The uniformity in temperature is inconsistent with the size of the universe. Two areas at opposite ends of the universe cannot be in causal contact with each other because light cannot travel across the universe within the age of the universe. Therefore one side should not be in thermal contact and thus equilibrium with the other side. It is, therefore, either an unlikely coincidence that the CMB is all the same temperature or there is deeper physics causing this phenomena.

The prevailing theory to explain this phenomenon is inflation, which states that in the beginning of the expansion phase the universe underwent a time of exponential expansion. This expansion would cause objects that were in causal contact before inflation to become sufficiently separated for them to no longer be in causal contact. Therefore, before inflation, the CMB could have been in causal contact allowing its temperature to become uniform, and then inflation expanded it to the signal seen today.

Inflation also solves other problems in cosmology including the existence of magnetic monopoles. Theory predicts that magnetic charges should exist in nature, however, none have been found. Inflation predicts that if monopoles exist their density will have been reduced to almost zero due to the exponential expansion of the universe, which would explain why none have been found. Inflation also predicts a flat universe. Current measurements show that the universe is very close to completely flat, but in order to achieve this without inflation the density parameter would have to be incredibly close to one, which is unlikely. If inflation occurred, any curvature the universe had before inflation would be stretched out so much that the radius of curvature would become large enough to assume the universe is flat.

To study inflation and the early universe, we must look past the CMB, but the universe was opaque at that time. This makes direct detection of these times impossible because no particles at these times could freely propagate. However, these particles can interact with light which will cause patterns to form. Therefore, the photons that comprise the CMB interacted with these primordial particles and thus contain information from pre-CMB eras. This makes CMB is the only probe to times before photon decoupling making it the most important tool for the studying of the early universe.

The CMB as already provided evidence for inflation. As mentioned above, it is very unlikely that the temperature of the CMB would be so uniform unless the photons were in causal contact then rapidly expanded out of it. Also, inflation predicts the existence of small energy perturbations caused by expanding quantum energy fluctuations to macroscopic scales. These variations can be seen in the anisotropy of the CMB temperature.

Currently research is looking for more evidence for inflation in the CMB. One method is to look for evidence of gravitational waves in the polarization modes of the CMB. The CMB contains two types of polarization named analogously to electrostatic and magnetostatic fields. One type is curl-free, called E-modes, and the other type is divergence-free, called B-modes. The E-modes originate from Thomson scattering of photons after inflation. The signal from E-modes are stronger than the ones from B-modes. The B-modes could originate from gravitational waves that are thought to have been present in the universe before inflation, but, they can also be observed when E-modes get warped by gravitational lensing.

Currently, researchers are trying to find the B-modes caused by gravitational waves in the very early universe. If inflation did occur, these gravitational waves would be stretched out by the rapid expansion of the universe to measurable B-modes in the CMB. These signals are weak, therefore foreground signals from dust, gravitational lensing, and other effects must be carefully taken into account to cancel out any effects that are not caused by gravitational waves.

Measuring these signals is done with a polarimeter which is a rotating half wave plate (HWP). The HWP modulates the polarization of the incoming signal. If a systematic error has a different frequency it can then be found and subtracted out from the data.

The primary source of atmospheric noise comes from Kolmogorov turbulence. In the atmosphere large scale eddies form in the air. These then fracture and break into smaller eddies. Eventually, the eddies become small and dissipate. This process releases energy that creates $1/f$ noise covering the CMB signal which is very small. But, Kolmogorov turbulence results only in variations in intensity not polarization. Therefore, if the polarization of incoming light is modulated over time, the large noise from Kolmogorov turbulence will become white noise near zero in frequency space. The signal from the CMB is polarized so it will not be cancelled by modulating the polarization. This results in a detectable signal despite large atmospheric background.

1.1 Superconducting Bearings

There have been several experiments that use polarimeters to measure the CMB. Some of these experiments, such as EBEX[2] and MAXIPOL[3], used superconducting bearings in their polarimeters.

Superconducting bearings utilize the Meissner Effect to create near frictionless bearings. Superconducting bearings consist of a type II superconducting ring with a ring magnet placed over top of it. When the superconductor reaches critical temperature, the Meissner effect locks the magnet in place with flux pinning, which is a phenomena caused by magnetic fields penetrating superconductors. At temperatures above a superconductors critical temperature, magnetic fields can penetrate the superconductor. When a type II superconductor is cooled it expels most of the magnetic fields. However, it can also capture magnetics fields that pass through it in small local regions and lock these fields in place. This traps the magnet in a fixed position above the superconductor. But, the magnet can still spin about its z-axis because of the angular symmetry of the ring magnet. This creates a bearing. If the system is placed in a vacuum then there is no air resistance or friction acting on the spinning magnet, creating a near-lossless bearing. The only losses are due to inhomogeneities in the magnet and the superconductor which cause asymmetries in the flux pinning. The pinned fields want to stay in the same place, but if the slightly asymmetric system is rotated they will be forced to move. The flux pinning will resist the motion of the spinning of the rotor.

There have also been studies to look at the properties of these bearings. It has been shown that the coefficient of friction of a superconducting bearing is on the order of 10^{-6} when operating in a liquid He cryostat and it decreases with temperature. The coefficient of friction can be further decreased by shimming the magnet with thin strips of steel to fix inhomogeneities in the magnet.[3]

Superconducting bearings require a cryogenic vacuum to minimize friction. Luckily, CMB polarimeters also need to work under these conditions to minimize losses and noise. This, coupled with the minimal friction of these bearings, make them the ideal for use in CMB polarimeters.

1.2 Induction Motors

While superconducting bearings have been used in CMB polarimeters to decrease frictional losses, there has not been an optimal solution to minimizing losses in the drive system. The EBEX experiment used a belt drive to turn the waveplate[2], but method has inherent losses due to friction. MAXIPOL used a half gear to flick the rotor[3]. When the rotor is at rest a half gear can interact with a gear on the rotor. The half gear can then be quickly rotated by 180 degrees causing the rotor to turn and the half gear to disconnect from the rotor. But, there is no continuous drive force so the rotor will decelerate and eventually stop due to losses in the bearing. This method reduces friction but causes other problems because the rotor is constantly changing its angular velocity making the data harder to interpret.

I propose using an induction motor to drive the polarimeter. Induction motors use sinusoidally changing magnetic fields on a stator to rotate a rotor. This means induction motors do not require any contact to drive the motor so he rotor will spin with a constant angular frequency and there are no losses due to friction . The primary losses in induction motors come from the moving magnetic fields causing eddy currents. But, these currents can be minimized by choosing materials that have low conductivity and slitting the materials. The eddy currents need to move throughout the material. If two slits are made that are deeper than the penetration depth of the magnetic field, then the eddy currents will not be able to pass the slits. Therefore the slits limit the size of the eddy currents and thus decrease the power lost.

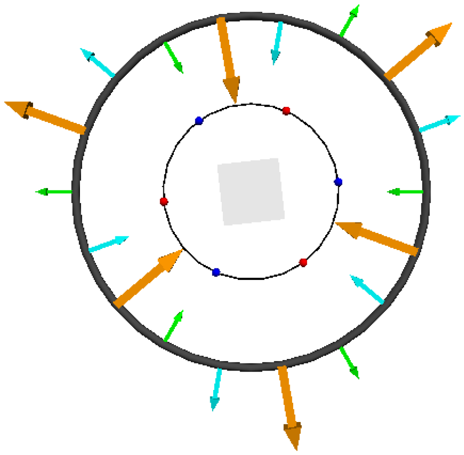

Figure 1: Map of the magnetic moments of the solenoids at a point in time in a three phase induction motor. The arrows represent the the direction and magnitude of the solenoids' magnetic moments and the color represents which solenoids are wire together. The dots on the inner circle represent the magnets on the rotor. The blue ones have their magnetic moments pointing towards the center and the red ones have their moments pointing radially outwards. A single phase motor would use only one set of arrows.

Induction motors use solenoids on the stator to attract or repel permanent magnets on the rotor to force the rotor to spin. In order to work, the magnets on the rotor must be properly aligned. The magnets need to be evenly spaced and be arranged such that magnets on opposite sides of the rotor have opposite poles facing radially outward. This makes each pair look like a bar magnet placed across the rotor with the center cut out. This is necessary to preserve the symmetry of magnetic dipoles. This symmetry means there will always be an even number of magnets on the rotor. Adjacent magnets must also have opposite poles facing outwards to ensures that adjacent magnets will not be attracted to or repelled from the same solenoid on the rotor at the same time. In fact, because dipole moments are opposite, one magnet will be attracted to a solenoid and the other will be repelled. This doubles the strength of the force on the rotor. This criteria forces there to be an odd number of pairs of magnets.

To understand the drive system of induction motors, it is easiest to first look at single-phase induction motors. The rotor is driven by magnetic fields created by a ring of solenoids on the stator. The solenoids change the direction of their magnetic moments sinusoidally. The rotor spins inside the stator with its magnets lined up with the solenoids on the stator. The solenoids are wired such that adjacent solenoids have opposite magnetic moments. As a drive magnet on the rotor approaches a solenoid, it is attracted to it, then, once it passes, the solenoid's magnetic field switches direction and repels the magnet towards the next solenoid. The next solenoid has the opposite magnetic moment in a single phase motor so it attracts the magnet. The switch in magnetic field will also cause the first solenoid to attract the next drive magnet because the magnet's moment faces the opposite direction as the one that just passed. This process of attracting and repelling applies a continuous torque on the motor.

This simple analysis looks at one-phase induction motors. One phase motors only require a single sine wave input current to power the solenoids. The opposite magnetic moments can be created by changing which way the current runs through the solenoids. However, it is preferable to use a three phase induction drive system. This operates on the same basic principle except each single solenoid is replaced with three solenoids whose sinusoidal currents are phase shifted by 60 degrees therefore each set of three spans 180 degrees (figure 1).

When a drive magnet approaches a set of three solenoids all three attract the magnet. As the magnet passes the first solenoid, the moment of the first decreases to zero and stops pulling the solenoid. As the magnet passes the first the second and third solenoids are still attracting it. When the magnet reaches the second solenoid, the current passing through the second goes to zero. Now the first solenoid is repelling the magnet and the third solenoid is attracting it. Lastly the magnet passes the third. This time the third solenoid has zero current, first two solenoids in the set are repelling the magnet, and the solenoids in the next set are attracting it. Therefore the magnet gets pulled and pushed across each three solenoid set into the next in a continuous cycle. Three phase induction motors run better than single phase because the difference between the magnetic fields of adjacent solenoids is smaller than with single phase motors. This causes the pull on the rotor to be much smoother, which results in a steadier angular frequency.

I have designed and tested a small scale prototype induction motor. I have also designed a prototype using a superconducting bearing.

2 Induction Motor Prototype

2.1 Circuit

The solenoids were powered by a circuit designed to take in a DC voltage from 0 to 2000mV and output three sine waves of the same frequency and phase shifted from each other by 60 degrees. The frequency of the sine waves is linearly proportional to the input DC voltage. Therefore their frequency can be changed by varying the input voltage. However, there is a threshold voltage over which the frequency will not increase[4].

This allows the user to accelerate the motor by slowly increasing the DC voltage which slowly increases the output frequency of the sine waves. If the magnetic fields of the solenoids are changing slightly faster than the angular frequency of the rotor, the rotor will accelerate to align the magnets with the minima of the magnetic fields. Therefore, once the motor is spinning, increasing the input voltage will increase the frequency of the motor. By the same logic, decreasing the input voltage will decrease the angular frequency of the rotor. The angular frequency of the rotor is a third of the angular frequency of the sine waves. This is due to the number of solenoid sets in the motor.

2.2 Room Temperature Model

The first generation of the motor was designed to develop and test the induction drive system at room temperature. This motor did not use a superconducting bearing but instead used a mechanical bearing. The mechanical bearing required no cooling or complex set up to run. Therefore tests could be performed quickly and easily.

The components of the room-temperature model were 3D printed using ABS plastic (see appendix A). This fabrication method was chosen because it is cheap and quick and also because the room temperature parts were not put under any stress therefore strength and durability were not primary concerns.

It is difficult to start the motor. Currently the motor is started by starting the DC voltage at zero and slow increasing it. But this method only starts the motor one in fifteen times. I found it easier to start the motor if I spun it slightly before increasing the voltage. With the initial spinning, the motor could be started about one in six or seven times. If this spinning could be reproduced without touching the motor it could help increase the likelihood of staring the motor. There may be a way create some initial motion by pulsing strong currents through the solenoids before trying to start the motor. However, once the motor is running it is easy to speed up and slow down by varying the magnetic field frequency with the circuit. When changing the frequency, it is important to not change it too fast. If the frequency of the sine waves rapidly changes, then the drive magnets become misaligned with the magnetic fields. This causes the rotor to decelerate and stop.

Once spinning the rotor can spin smoothly from 1Hz to 5Hz, but behaves the best at frequencies above 1.5Hz. I found that in order to get smoother motion at lower frequencies it was best to first accelerate the rotor to a higher angular frequency then decrease to the desired one. Also, it takes 15 to 30 seconds after adjusting the magnetic field frequency for the rotor's angular frequency to lock in place and the motion to become smooth.

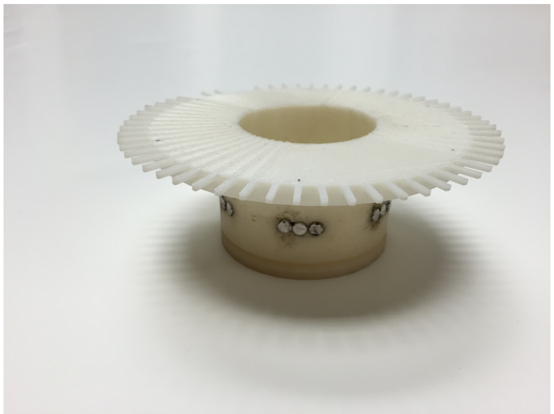

Figure 2: Room temperature rotor. The drive magnets are groups of three cylindrical magnets. The photo-interrupter is connected to the top of the rotor.

2.2.1 Rotor

The body of the rotor is a 2.5" diameter, 1.5" tall cylinder (figure 2). The top inch of the cylinder is hollowed out to remove material and make 3D printing easier. Centered in the bottom there is a 0.5" diameter, 0.125" deep circular recess for a mechanical bearing to be placed. Above this there is a 0.375" hole that goes through the bottom of the rotor. This provides clearance for the stator to connect to the bearing. 0.75" above the bottom of the rotor there are 6 sets of 3 adjacent 0.188" diameter holes to hold the drive magnets. There must be three adjacent magnets to make every set of drive magnets span from one solenoid to the next on the stator.

Initially, the rotor was designed using only one magnet in each set. The movement of this model was choppy if it even moved. Most of time, this model wobbled back and forth with the magnets stuck between two solenoids. I believe this behavior was caused by the the magnets falling into a local minimum of the magnetic fields between solenoids. In the minimum, the magnets would never experience enough force to pull them out before the solenoids changed magnetic moments. Adding the extra magnets forced at least one end of each set to be close to a solenoid at all times. This resulted in a stronger force on the magnets which made it more difficult for the magnets to become stuck in a local minimum. This model spun smoothly and more consistently.

The room temperature model was designed with a photo-encoder on top of it. This consisted of a 4.25" diameter, 0.25" thick disk on top of the rotor. The top, outside edge of the disk has sixty 0.375" long, 0.062" thick spokes protruding radially outwards. These act as the photo-encoder that is used with a photo-interrupter on the stator to measure the angular velocity of the rotor.

2.2.2 Stator

The stator (figure 3) is a hollow cylinder with an inner diameter of 2.625" and outer diameter 4.625". This is only slightly larger than the outer diameter of the rotor to allow the magnets on the rotor to be as close as possible to the solenoids in the stator. On the outside there is a ring of 18 evenly spaced 0.75" deep, 0.375" diameter blind radial holes that end 0.125" short of the inner diameter of the stator. These holes hold the solenoids and are long enough to completely enclose the solenoids except for a short nub that sticks out to allow the solenoids to be removed. The bottom of the stator is closed off and a rod protrudes up the center to hold the mechanical bearing. The rod holds the rotor such that the center of the magnets line up with the center of the solenoids. After the primary feature were solidified the final design was changed to remove extra material. This saved time when 3D printing the part. Attached to the top of the stator was a jig to hold a photo-interrupter

The solenoids are placed into the blind holes and wired in three sets each wired in parallel. Each set consists of all the solenoids that have the same phase or are 180 degrees out of phase. The two phases can be achieved on the same circuit by switching the order of the leads on a solenoid causing the current to run the

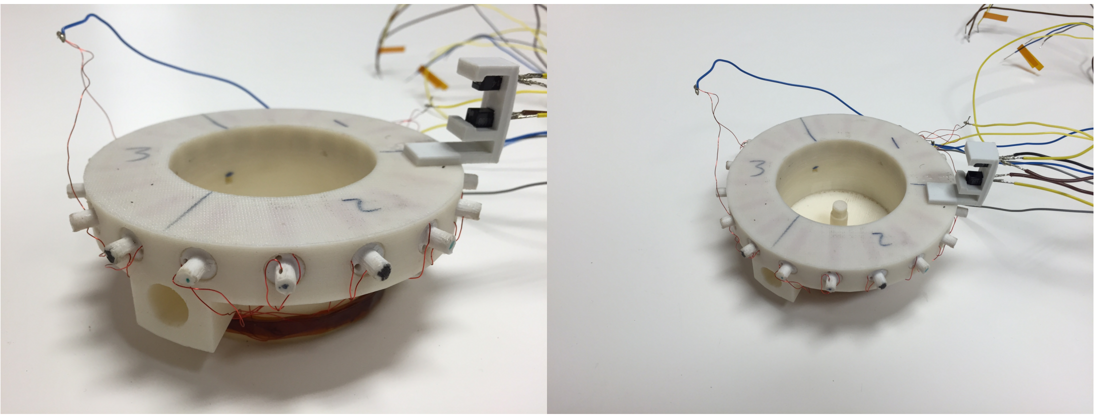

Figure 3: Stator for the room temperature prototype with solenoids inserted. The mount on the right side holds the photo-interrupter. Left: The hole beneath the bobbins was intended to test a locking mechanism, but it was never used. Right: The rod in the middle connects to the mechanical bearing and holds the rotor.

opposite direction through the solenoid. Each set is put in the rotor with two spaces between each solenoid. Therefore every third solenoid is part of the same set. The three sets take in sinusoidal currents that are phase shifted by 60 degrees.

2.2.3 Solenoids

The main shaft of the solenoids is 1" long and 0.25" in diameter. One end of the solenoid is a disk that is 0.375" in diameter and 0.125" thick. Five-eighths of an inch above this side there is another similar disk. The two disks create a bobbin for wire to be wound on. There is 0.125" on the main shaft remaining. This end allows the solenoid to be grabbed with pliers to be pulled out of the stator (figure 3). The bobbin outer diameter was chosen to be the largest size possible that would fit in the stator and the main shaft diameter is the smallest possible size that still maintains some strength; any smaller and the bobbins break when the wire was wound on. The overall length was chosen to be a good working size and exact size in not important because the strength of a solenoid is proportional to the number of coils per unit length.

The bobbins were wound with 36 gauge copper wire using a CNC coil winder[5]. The coil winder held a spool of wire with the working end passed through a needle then secured to a bobbin. The bobbin was clamped in a chuck and rotated. As the bobbin rotated a motor would move the needle back and forth to create an even winding across the entire bobbin. Afterwards the free end was taped down to prevent the solenoid from unraveling.

2.3 Cryogenic Model

The second generation of the induction motor was designed to test the induction motor with the superconducting bearing (see appendix B for schematics of parts). It was designed for testing at five Kelvin and at room temperature. The motor needs to operate at room temperature so the system can be tested before it placed in a cryostat.

The superconducting bearing consists of a YBCO ring[6] that will be attached to a baseplate and a ring magnet that will be attached to the rotor. YBCO was chosen because it is a high temperature type II superconductor. It has a critical temperature of 93K. This is above the boiling temperature of liquid nitrogen, 77K. This will allow the bearing to be tested in a liquid nitrogen bath before testing the motor at five Kelvin in a cryostat.

The parts for the cryogenic model are made out of aluminum so they could withstand this temperature range. This model consists of several parts that are all attached to a large base-plate. The rotor and stator have been modified slightly from the room temperature model to fit the cryogenic bearing but are fundamentally the same. This model must include a lock mechanism to hold the rotor in place before the temperature becomes low enough for the Meissner effect to hold the rotor.

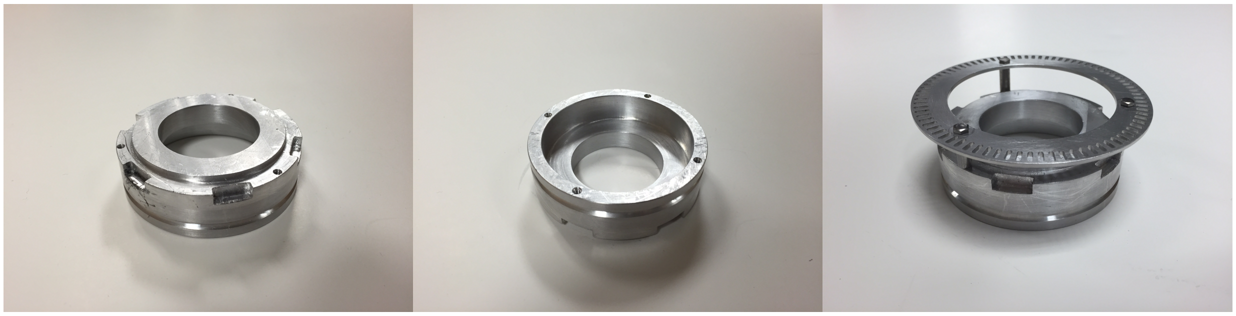

Figure 4: Left: Top of the rotor for the cryogenic model. There are six rectangular recesses for the drive magnets. Middle: Bottom of the rotor. The recess is to hold the ring magnet for the superconducting bearing. Right: Cryogenic rotor with the photo-encoder installed. The spacers raise the photo-encoder above the stator.

I tried to test this model at room temperature using a mechanical bearing. Unfortunately, I did not get it to rotate. It did wobble back and forth which suggests that it is trying to move. The room temperature model behaved similarly when it was trying to move, so it is likely that the cryogenic model needs a few minor changes to run. It may have not have moved because the bearing used did not turn completely smoothly. This created more friction which the motor may have not been able to overcome. Also, the rotor for this model is heavier than the room temperature model. Therefore more energy needs to be put into the system in order to accelerate it. The solenoids may not have had enough power to turn the rotor far enough for the next solenoid to catch it. This could be solved by putting more windings on the solenoids or increasing the maximum current passing through them to increase the maximum magnitude of the magnetic fields.

2.3.1 Rotor

The cryogenic rotor is almost identical to the room temperature rotor. It is a 0.875” tall ring with 2.875” outer diameter and 1.563” inner diameter. In the bottom there is a 0.5”, deep 2.375” diameter recess for the ring magnet. The top of the rotor has a radial recess to raise the top slightly. This creates a platform on which a waveplate can sit (figure 4).

On the top outside edge there are six evenly spaced rectangular recesses that are 0.5” long, 0.156” tall, and 0.125” deep. These recesses are to hold the drive magnets. The magnets for the cryogenic rotor are 0.5” by 0.125” by 0.125” rectangular neodymium magnets. These magnets span two solenoids like the room temperature rotor, but they only need one magnet to do so, instead of using three.

Also, on top of the rotor are three vertical, evenly spaced, tapped, blind holes. These are used to attach an photo-encoder wheel which will be used to measure the angular velocity of the rotor when it is spinning.

On the bottom of the rotor there are four vertical, blind holes spaced 90 degrees apart. These are used to mount a jig to hold a mechanical bearing. This allows the motor to be run without the superconducting bearing

Around the outside of rotor, 0.25” from the bottom there is a triangular groove. This groove fits the end of the arms of the locking mechanism. When the locking mechanism is activated the tips of the arms slide into these grooves. A triangular slit was used so the rotor can be slightly misaligned with the arm but the arms will still fit properly.

2.3.2 Stator

The stator is a 0.625” tall ring with a 3.5” outer diameter and a 3” inner diameter. Although the inner diameter is larger than the room temperature stator, the cryogenic stator uses much less material as can be seen in figure 5. Minimizing the material of the stator allows the stator to cool down faster. There are 18

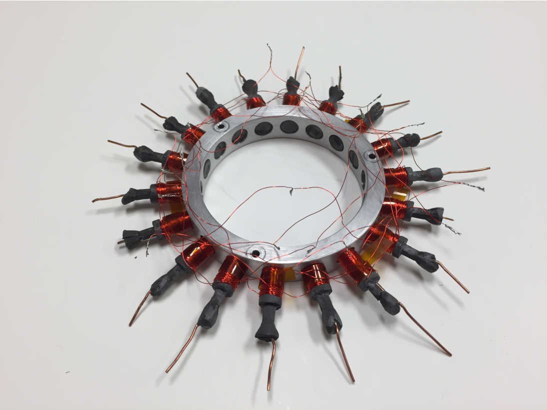

Figure 5: Stator for the cryogenic model with wound solenoids inserted into the radial holes

Figure 6: Cryogenic solenoid bobbin. The bobbin is made of stycast 1266 epoxy.

through holes in the radial direction to hold the solenoids. Unlike the room temperature model these holes do not completely envelope the solenoids. Instead they hold one end of each solenoid and the rest hangs outside. This was determined to be enough to secure the solenoids. Initially, blind holes were considered to ensure the bobbins could not move and hit the rotor and also to force the bobbins all be the same distance from the center, but blind holes were impractical to machine so through holes were used. The disadvantage of using through holes is they can allow the solenoids to move too far inwards and hit the rotor. However, because the bobbins will be glued in place, the likelihood of this happening is small. Also, the bobbins may be unevenly placed, but I suspect that small changes in the distance will not cause a major effect on the motion of the rotor. Future models should use blind holes to minimize any such effects, but for the prototype it was deemed unnecessary.

The stator has three small holes spaced 120 degrees apart through the top of the ring. These are to attach the stator to three legs. The legs raise the stator up 1.625" to the proper height and they will be attached to the base-plate.

2.3.3 Solenoid Bobbins

The cryogenic solenoids have the same design as the room temperature ones but are not made of plastic (figure 6). Instead they are made of stycast 1266 epoxy loaded with stainless steel powder. The material was chosen because it acts well at low temperatures and because it is a microwave absorber. The microwave absorber properties allow the bobbin to not heat up even when microwaves are shone on it. However, this

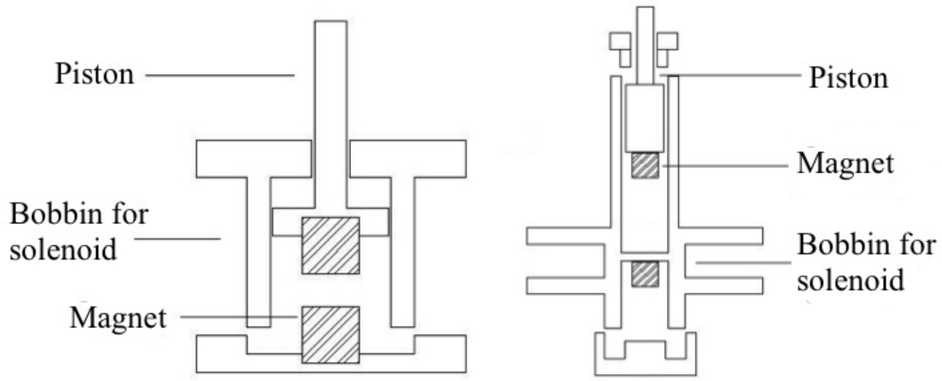

Figure 7: Right: The initial design of the locking actuator. Left: The final design of the locking actuator. The final actuator has a wider and shorter solenoid than the initial. The springs are not shown in these diagrams.

material has a low thermal conductivity so it does not cool down easily. To help with cooling, a copper wire was inserted into all the bobbins. The wire can be connected directly to a heat sink. Future generations of bobbins may need to be made of a different material to improve cooling.

The bobbins were made using silicone molds. The molds were made by 3D printing positives then casting negatives out of silicone. The epoxy was watered down with acetone then poured it into the silicone molds. Then a copper wire was inserted through the bobbin lengthwise. The acetone was then boiled out before the epoxy could dry.

To run at both 5K and room temperature, the wire used for the solenoids will be superconducting wire with a copper casing. The casing conducts at room temperature and the superconducting wire allows for very low resistance at 5K. This means there will be minimal power loss in the solenoids and minimize heating. Also, the low resistance allows the motor to run with very low voltage which further decreases the power lost and also makes it easier to run on a simple power source.

2.3.4 Locking Mechanism

The first generation locking mechanism was a push-pull magnetic locking actuator (figure 7). These consisted of two small magnets inside a solenoid, one would be fixed to a wall and the other would be attached to a movable piston. The magnets are aligned such that their magnetic moments are parallel so they attract each other. But, there is a spring holding the piston away from the wall.

When the solenoid turns on it creates a magnetic field that can move the magnet on the piston in two possible directions. The solenoid can push the two magnets together against the spring. If the magnetics get close enough to each other then the magnetic force will dominate the spring force causing the magnets to stick together, retracting the piston. The solenoid can then be turned off and the piston will stay in this position. From this position the solenoid can be turned on with the opposite current. This forces the magnets apart. Once the magnets are far enough apart the spring force dominates and holds them apart when the solenoid is turned off.

The first iteration of this locking mechanism used a bobbin with a 0.75” long bed for the solenoid with a 0.56” outer diameter and 0.4” inner diameter and used 0.1875” cube magnets. One end of the bobbin is fixed and the other can be removed so the magnets, spring and piston can be put in place. With the magnets and spring in place and the end cap on, wire can be wound around the bobbin to make it a solenoid.

This design failed to work because there is a critical point in the center of the solenoid. Depending on the direction of the current the magnet on the piston would either be attracted or repelled from the center. Therefore the magnet could only move from fully extended to the middle of the solenoid. This caused the

Figure 8: Stainless steel bellows for the locking mechanism. The arm on the right side tapers to a point to fit in the groove on the rotor. The left side is an adapter to fill the bellows with nitrogen gas.

magnets to never move close enough together to overcome the spring force. The piston would retract slightly but would extend as soon as the solenoid was turned off causing the actuator was stuck in the extended position.

Multiple tests were then performed on the actuators. I tested to determine where the magnet had to be placed so the solenoid could apply the maximal force. This occurred at the end of the solenoid. I also tested the best placement for the fixed magnet which was approximately at the center of the solenoid. It also was determined that the system worked best if the two magnets were slightly separated when the piston was retracted. This decreased the magnetic force making them easier to pull apart.

The last iteration used the results of these tests and use the critical point that caused the first generation to fail. The bed of the bobbin was smaller, 0.25" long with the same diameter, but it was designed with a larger outer diameter to hold more coils. Also, the stationary magnet was put on the outside of the bobbin wall so there would be a thin wall between the two bobbins when the piston was in the retracted position.

It took several variations to correctly position the stationary magnet such that the actuator worked consistently. The working actuator could be retracted and extended and the piston would stay in position when the solenoid was turned off. But, the actuators were not strong enough to hold the rotor in place. In the extended position the spring force dominated and by itself would have been enough to lock the rotor in place but the magnetic force counteracted the spring force and decreased the net force. The net force was not enough to hold the rotor in position before the superconductor reached critical temperature. For this reason the idea was discarded. I believe that it is possible to engineer an actuator with this basic design that would have enough force, but that would be another project in itself.

The current locking mechanism is a passive pressure regulated locking mechanism which is designed to be used in the cryogenic model. The locking mechanism is a set of three actuators spaced 120 degrees around the rotor. Each actuator is a steel bellows with an aluminum rod attached one end. The rod is tapered at the end to fit into the groove in the rotor (figure 8). The bellows are filled with nitrogen gas. When placed in a vacuum the internal pressure causes the bellows to expand so the arm is pushed forward into the groove on the rotor. As the whole system cools to 5K, the vapor pressure will decrease in the bellows. Eventually, the temperature will drop below the boiling point of nitrogen and the gas will become a liquid. This causes the vapor pressure to vanish and the bellows will retract freeing the rotor. When the system is heated back up, the temperature will rise above the boiling point and the nitrogen will become a gas increasing the vapor pressure. The bellows will then expand and clamp the rotor.

Nitrogen was chosen because its boiling point is 77K which is below the critical temperature of YBCO, 93K. Therefore as the system cools the superconductors will reach critical temperature and thus locking the rotor in place with the Meissner effect before the bellows release the rotor. Also, when warming up the motor the actuators will grab the rotor before the superconductor loses its superconductivity.

Other locking mechanisms were considered, but this one was chosen because it acts passively. Other systems require some drive mechanism such as a stepping motor. These have moving parts and require

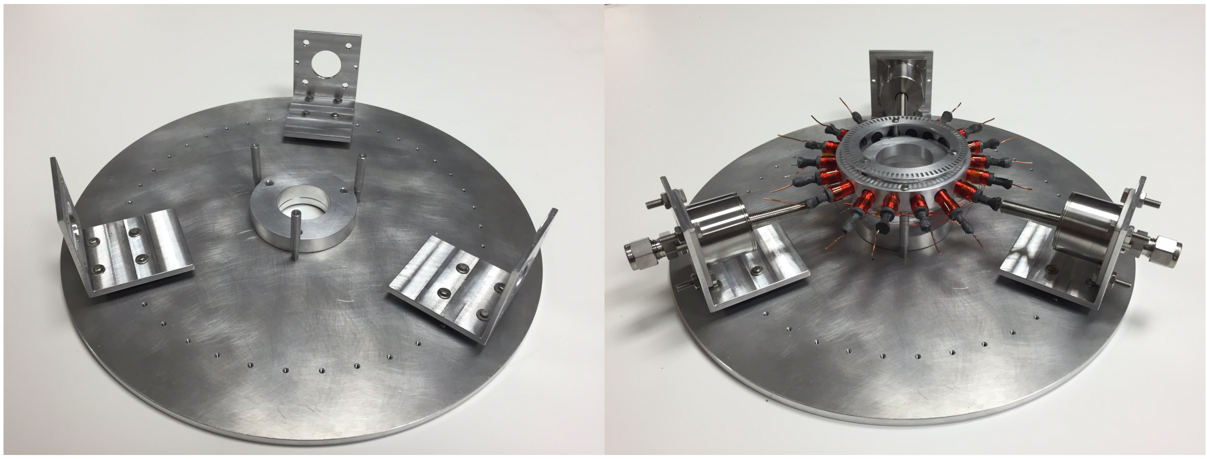

Figure 9: Left: Baseplate with the superconductor platform, legs to hold the stator, and braces for the actuators. Right: Full assembly of the cryogenic prototype.

electricity. Both of these create inefficiencies that introduce heat into the system. Also, these methods require a control system to activate them at the appropriate time. This creates an added layer of complexity that the bellows do not have.

The downside to using this method is the whole system needs to be heated up in order to clamp the rotor. Other methods can activate at any temperature. Another disadvantage is the bellows will release the rotor at 77K, therefore the rotor cannot cool down below that temperature.

2.3.5 Assembly

The cryogenic motor is assembled on a base-plate. The base plate is a 0.25" thick aluminum disk with a 13" diameter. Everything that attaches to the base-plate using screws into tapped holes (figure 9).

There is a 1.5" hole in the center of the base-plate to allow light to pass through so the motor can be tested as a polarimeter. Just outside the center hole a 0.5" high, 3" diameter raised platform can be attached to the base-plate to hold the YBCO superconducting ring. The superconductor had to be raised up due to limitations on how far down the steel bellows could be placed. This platform can also be removed and replaced with a plastic mount to hold a mechanical bearing. The mechanical bearing allows the drive system to be tested without having to cool the motor.

1.75" from the center of the baseplate there are three holes to attach the legs of the the stator. The legs are 1.625" tall. Towards the outside edge of the base-plate are three sets of holes to attach an L-brace. The brace is designed to hold the locking mechanism. There is a ring of 40 tapped holes spaced 9 degrees apart 5" from the center of the baseplate. These holes are used to connect parts to the base plate with wire. This allows the baseplate to act as a heat sink. For example, the copper wires in the solenoids will be wired to these holes to help cool them.

3 Next Steps

Currently, only the room temperature prototype has only been tested and it had to be started manually. The next main step is to devise a method to start the motor more consistently. Currently the motor can start from rest only about one in fifteen times. With some changes, I hope to be able to start the motor one in ten times, which would be more practical.

Once a better method is devised, a circuit will need to be added so the motor can start itself. Work is currently being done to create this circuit. There are two steps to create the self-starting system. The first is creating a program that will increase the input voltage to slowly increase the output frequency. This is being done using a labjack. The main challenge with this is that the controller needs to increase the voltage at the proper time. If the frequency increases too fast the rotor cannot keep up and will stop. Therefore the controller needs to be able to know how fast the rotor is spinning. This can be done using a photo-interrupter and an optical encoder wheel. The photo-interrupter will send periodic signals to the controller which can interpret the time between pulses. The controller will then check the pulse time against what is expected given the current input voltage into the drive circuit. If they agree, the controller continues to increase the frequency, if not, the controller will set the voltage to zero and start over. I do not think that the rotor will need to be stopped before each trial start. In fact, the current method of starting the motor works best if the rotor is spinning slightly initially, so some movement could prove to be useful.

The controller must also monitor the currents of the output signals. Currently, at low frequencies the output current is too large. This causes the magnetic fields generated by the solenoids to be too strong which causes the rotor to quickly jump to the next solenoid, then slow down then quickly jump to the next. The force needs to be reduced to better match the angular frequency.

The can be done using a resister ladder. The ladder will allow the resistance of the outputs, and thus the currents, to be varied by applying current signals to the resistance ladder to create higher and lower resistances. At low frequencies the resistance can be set high to decrease the force on the rotor and has it speeds up the resistance can be lowered to increase the force.

Also, it is likely that when the cryogenic motor is in a vacuum it will require very little force to keep it spinning because of the lack of losses. In this case the output current can be decreased once the rotor reaches the desired speed. This will decrease the power usage of the motor and decrease the magnetic fields near the rotor. Both of these will decrease the amount of power lost in the system. Once again the controller to run the resistance ladder will need to know how fast the rotor is spinning and adjust accordingly.

Once the drive system is completed the whole system needs to be prepared to be put in to cryostat. This cryostat will allow the motor to be tested in a controlled, cold vacuum.

3.1 Future Tests

Several tests still need to be performed on the prototype. So far it has only shown that the induction motor works at room temperature. The next step is to test the cryogenic model at room temperature using a mechanical bearing. This is necessary to fix any bugs in the system. Then the motor should be tested with the superconducting bearing in a liquid nitrogen bath. This test will be used to fix an problems with the bearing. Next, the motor needs to be run in a cryostat. This will test the motor in the environment it is designed to work in. In the cryostat the temperature of the rotor should be measured to ensure that it does not heat up too much. If the motor becomes warm then thermal noise will overwhelm the useful data. It would also be worth while to accelerate the rotor up to the maximum frequency then turn the drive circuit off and let the rotor coast while the angular frequency of the rotor is measured. The angular frequency of the rotor will decay with time; the rate of decay will tell how much loss is inherent in the bearing. Another test is to run the run the motor for several days straight to test how robust the system is and how much wear the parts take. These tests should highlight any flaws in the design that will need to be changed.

3.2 Design Changes

After the cryogenic prototype is tested and shown to work, the next step will be to develop the next generation of the motor. The next generation will ideally be the full desired size for the polarimeter. This will have an aperture of about 11”. Making it larger should be a simple task; the drive system and layout will remain essentially the same but there will be more solenoids and drive magnets.

It may be necessary to take measures to decease losses due to eddy currents. To do this, the inside of the stator can be sliced vertically many times. The separation of the slices determines the size of eddy currents can form because the currents must travel in the metal. Therefore if the separation of the slits is small enough only small eddy currents can form which will reduce the power lost.

One major change for future generations is to change the superconducting bearing. Instead of having one magnet on the rotor and the superconducting tile underneath it, it would be ideal to have the superconductor going around the rotor. Also, the levitation magnet on the rotor will be replaced with an iron ring sandwiched between two ring magnets. This configuration has been shown to be stiffer which is desirable to quickly damp out any perturbations, but, this configuration will require the rotor and stator to be completely redesigned.

One potential problem with this design is that the drive magnets and solenoids will now be closer the superconductor. This could cause the Meissner effect to try to lock the drive magnets in place. This would create drag. Therefore it is important that the drive system is located far enough from the superconductor so the two do not interact. One possibility for this is to put the bearing at the bottom of the rotor and the drive system at the top.

4 Conclusions

The room temperature model proved the induction drive system works. The motor could turn smoothly from 1Hz to 5Hz. However, testing the cryogenic model at room temperature did not work. It showed signs that the rotor is feeling a force from the solenoids. I think that only a few minor changes need to be made to make it spin. One problem with the current model may be the mechanical bearing used for testing the cryogenic model felt like it had something suck in it which was causing it not to spin freely. This would make it more difficult to rotate the motor. Also, the currents may need to be increased to increase the force on the rotor. It may also help to try to test the rotor using the superconducting bearing by cooling it with liquid nitrogen. This could solve the problem of the extra friction from the bad mechanical bearing.

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Appendix A: 3D Printing

All the parts for the room temperature model were 3D printed using ABS plastic. 3D printers create objects by extruded a thin bead of molten plastic through a printer head. The printer builds up the object layer by layer. The first layer is printed directly onto a baseplate. The baseplate typically needs to be prepared with some sort of glue to help the plastic stick to it. Subsequent layers are printed on top of each other and the hot plastic melts the previous layer slightly to the two fuse together. 3D printers need to have a previous layer to print on, therefore if the part has an overhang, the printer must also print supports for the first layers of the overhangs.

The rotor and stator were printed using a Dimension Elite Fused Deposition Modeling printer[7]. This printer gives high quality parts and is capable of printing small details of about 0.063", such as the spokes on the photo-encoder. This machine prints with two materials: a structure material, typically ABS plastic, which is used to print the part and support material. The support material is used to create bases for structures that do not start at the bottom of the part. After the print, the support material is washed away leaving only the piece printed in the structure material. The downside to using this printer is the drawings of the parts had to be sent in to be printed by a third party which caused a longer printing time. Therefore this printer was not efficient for testing different designs. This printer also requires complicated pre-print and post-print work to set up and clean up the parts.

The rest of the parts, such as the bobbins for the solenoids and the prototypes of the push-pull locking mechanism, were printed using a Cubify Cube printer[8]. These are cheaper, tabletop printers that are marketed towards hobbyists. The parts produced by this printer are not as high quality as parts printed with the Dimension Elite printer. There are lines on the parts from the buildup of material and small details, about 0.05", tend to get blurred or enlarged. For the most part these imperfections were small enough to be insignificant or to be easily taken care of with sandpaper. One downside to using this printer is it only prints with one material. If support material is needed, the printer prints it out of the same plastic as the part. The support material needs to be removed with a knife after the part is finished printing. It is not a very clean nor elegant method, but the printers generally print the supports in a way that can be removed easily.

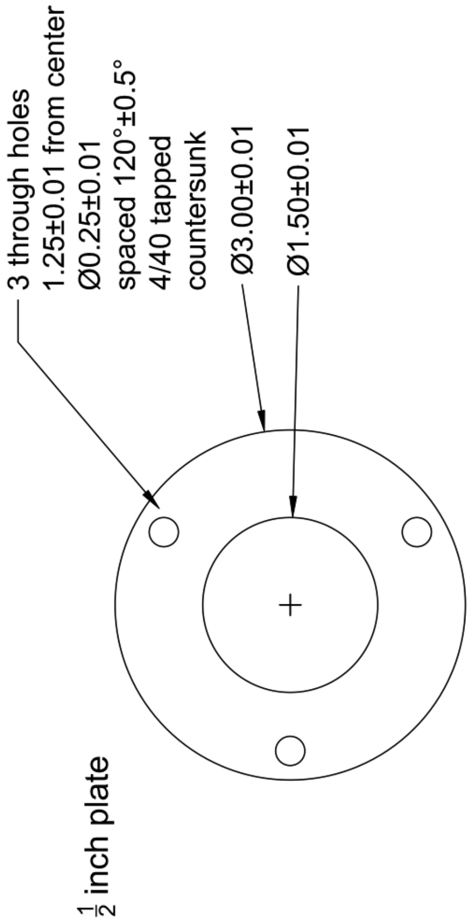
The Cube printers used spools of ABS plastic to print with. The spools were cheap and could print quite a few parts. I printed a new actuator every day for month and did not finish off a spool. Cubify does not specify the amount of material in each spool but a third party estimates that they contain 300 cubic centimeters of ABS plastic[9]. The Cube printer uses material efficiently by not printing solid objects. Instead the interior is a lattice that is mostly empty. The density of the lattice can be chosen before the print starts. This method of printing also cuts the printing time down substantially.

With the Cube printers, I had a few bad prints in which a section failed to stick, the print head got jammed with plastic, or the printer head started running into the part. Fortunately, errors in the print were easy to see while the part was still printing so at the first sign of a problem the print could be aborted and restarted. In general, failed prints were not a problem; there were only a handful of incidences of these out of the dozens of prints that I completed.

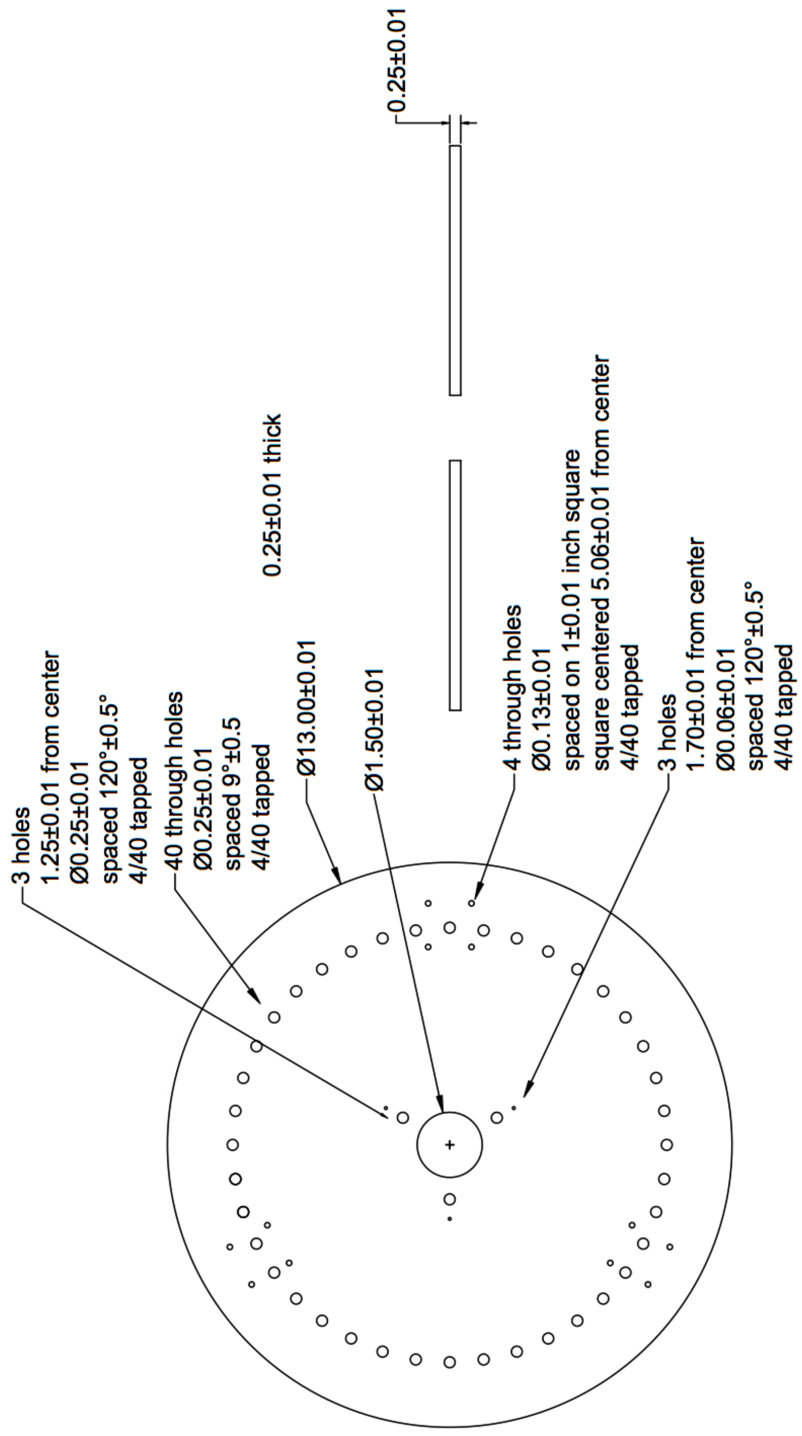
The Cube printer was useful for cheaply and quickly fabricating parts where quality was not a primary concern. This allowed me to print a part, test it, redesign it, and print a new one all in one day. This allowed for rapid development of the actuators because I could print around seven different iterations in a week.

Overall, the use of 3D printing was essential to rapidly develop parts and quickly create prototypes. The Cube printer, despite its flaws, performs well considering that it is designed for quick and dirty printing. It was essential in the development of the solenoid bobbins and the push-pull locking actuators. Without this printer it would have taken months to design the actuators instead of weeks, and they would have cost much more to make. The Dimension Elite FDM printer was also a valuable tool for printing cleaner final products and larger parts. 3D printing is a powerful tool when it is acceptable for parts to be made out of plastic. It is cheaper and faster than having parts machined and the quality is still good enough for prototypes.

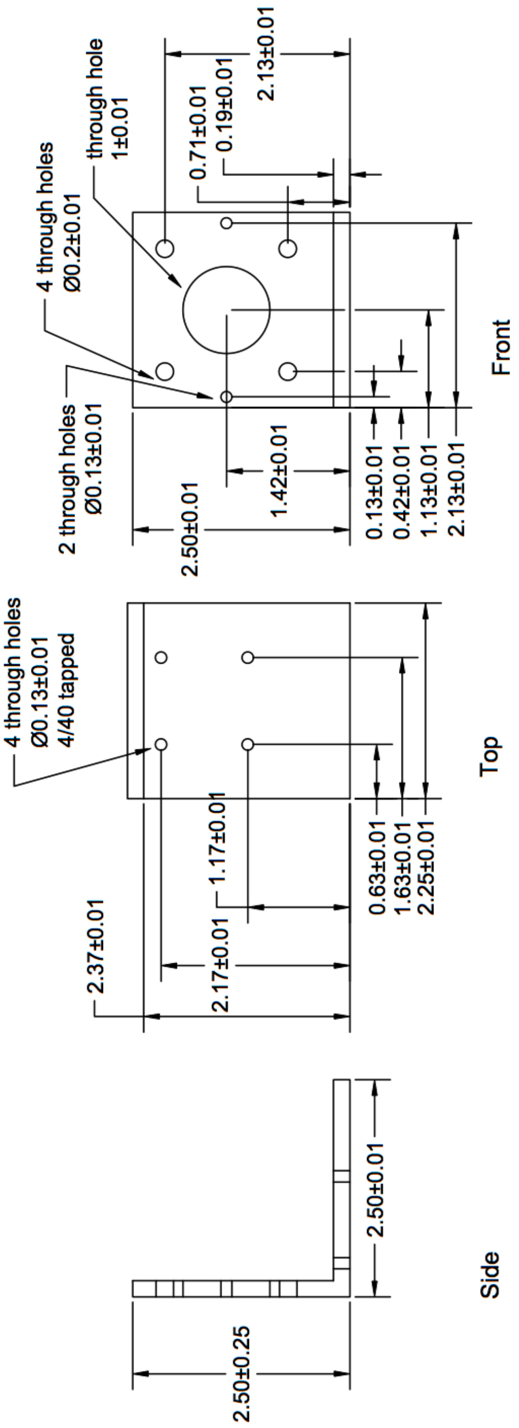
Appendix B: Technical Drawings of Cryogenic Model Parts



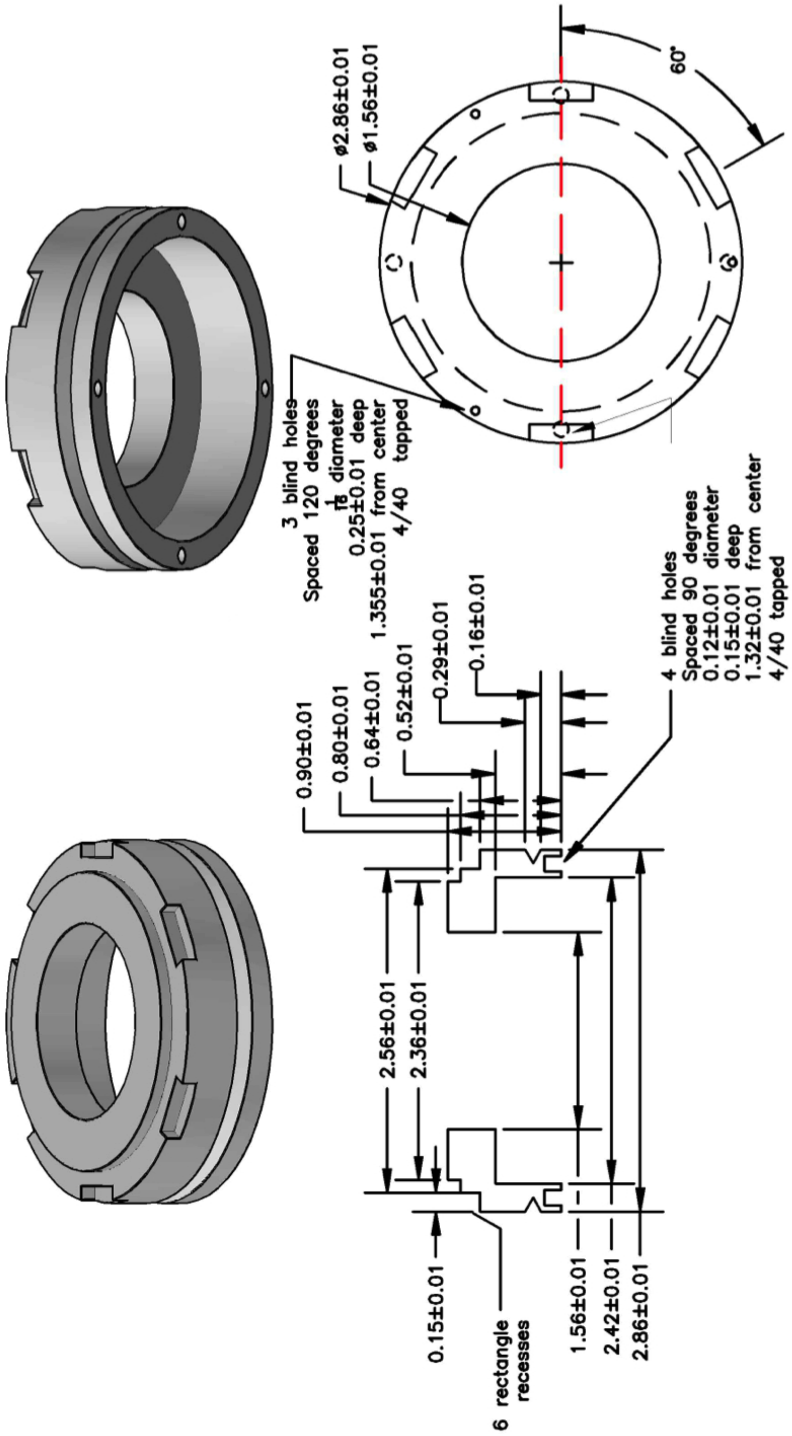
YBCO Ring Holder

3 holes
1.25±0.01 from center
Ø0.25±0.01
spaced 120°±0.5°
4/40 tapped
40 through holes
Ø0.25±0.01
spaced 9°±0.5
4/40 tapped
Ø13.00±0.01
Ø1.50±0.01
0.25±0.01 thick
4 through holes
Ø0.13±0.01
spaced on 1±0.01 inch square
square centered 5.06±0.01 from center
4/40 tapped
3 holes
1.70±0.01 from center
Ø0.06±0.01
spaced 120°±0.5°
4/40 tapped
0.25±0.01

Base Plate



Bellows Holder



Cryogenic Rotor

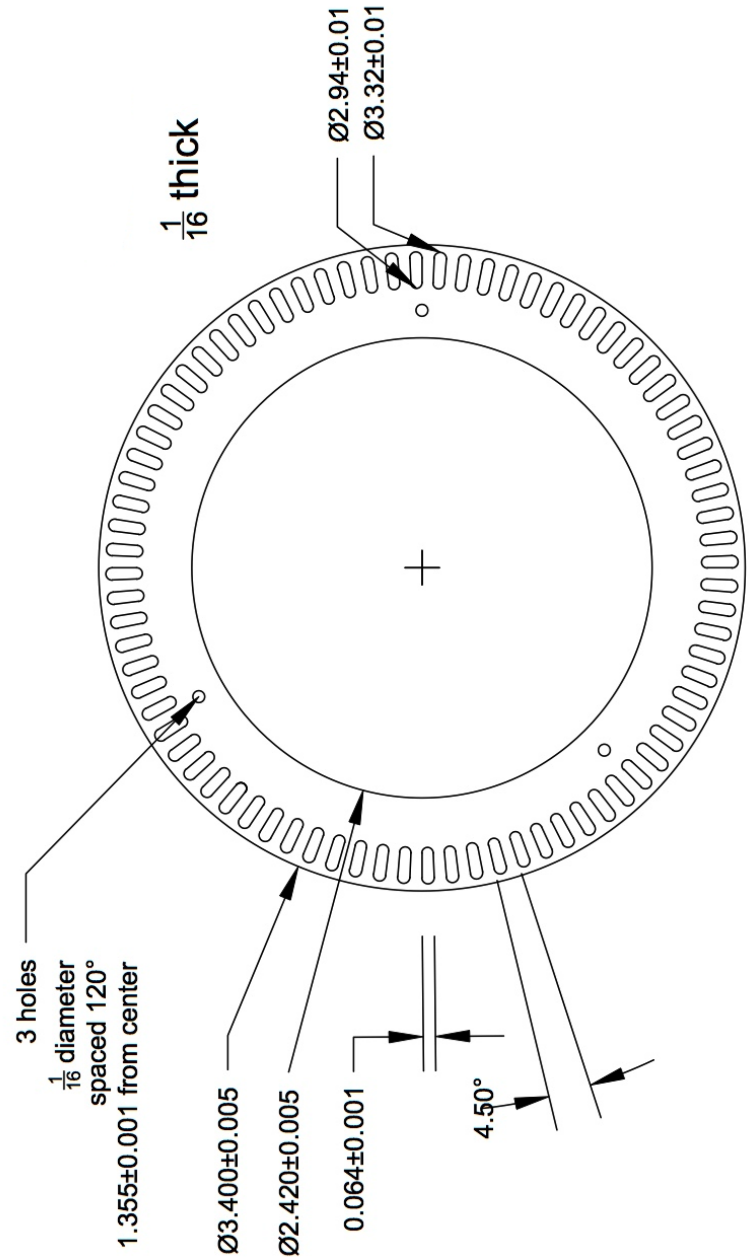
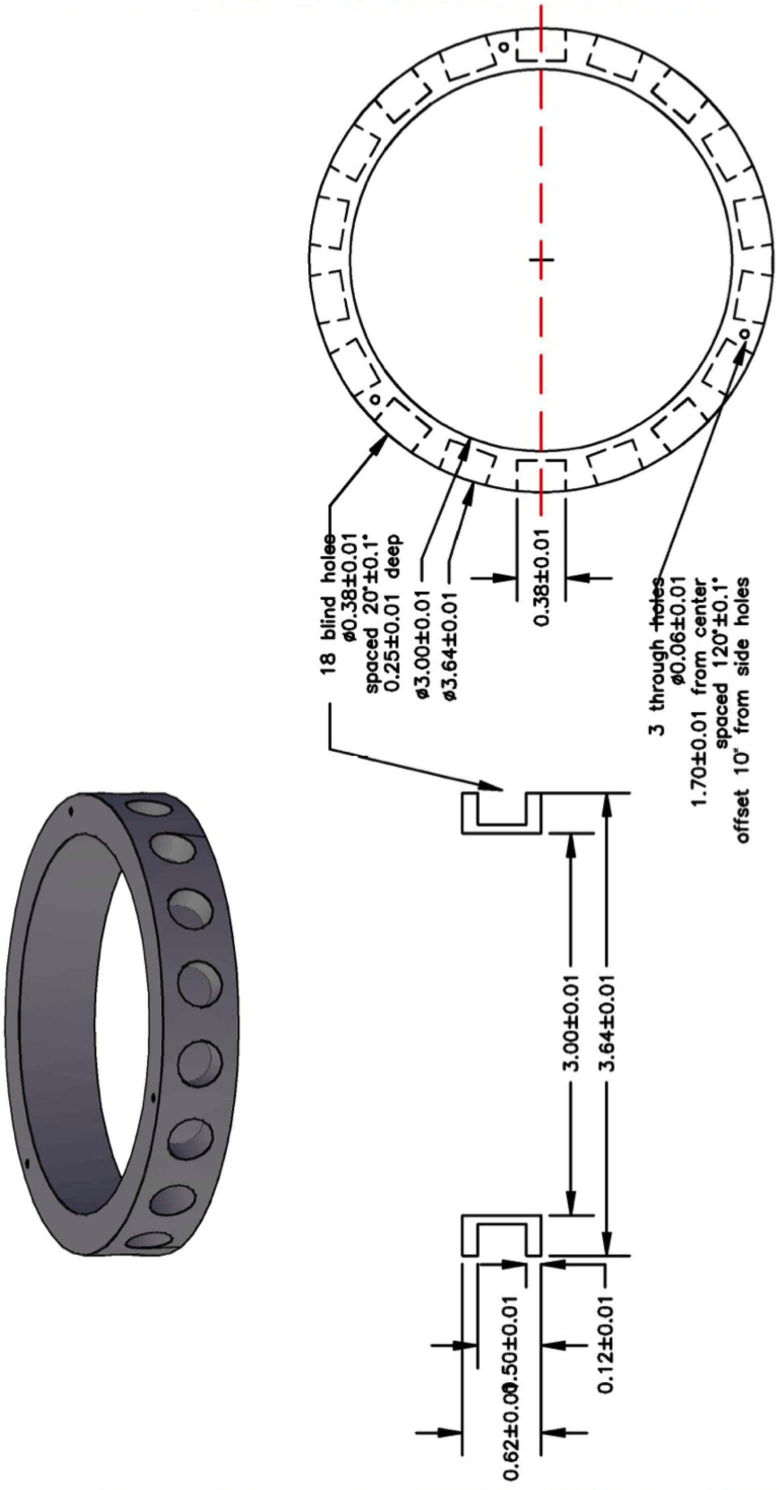


Photo-Encoder



Cryogenic Stator