Design and Modeling of Dark Matter Axion Detectors

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Abstract

Axions are a proposed cold dark matter particle. They are very light (10^{-5} to 10^{-3} eV) and decompose into microwave photons in a strong magnetic field (Axion). The goal of the Axion Dark Matter eXperiment (ADMX) is to detect these microwave photons and use their energy to calculate the mass of the axion. Fermilab's R&D program for ADMX is focused on making higher frequency cavities to scan for heavier axions.

Introduction

At current estimates, dark matter makes up 24% of the matter/energy in the universe. This estimate stems from observations of the rotation velocities of galaxies and other large structures in the universe. Their velocities suggest more matter than is observable. Since this missing matter does not interact with electromagnetic radiation very often, it was named dark matter. Many different dark matter particles have been theorized, and axions are one of these particles. The ADMX experiment uses tunable resonant microwave cavities to detect the microwave photons given off by axion decomposition. If the resonant frequency of the cavities (which is dependent on their diameter) is the same as the frequency of the microwave photons, the detection equipment registers a power spike. This spike can be used to calculate the mass of the axions.

Methods

The existing ADMX detectors scan a set frequency range and have excluded a mass range on the lighter side. Fermilab is working on higher frequency cavity R&D and tasked me with the design and 3D modeling of the detector cavities. My work will be used as a starting point for the implementation of cavities with higher frequency scanning ranges.

The objectives behind the high frequency cavity designs are as follows: allow for parameter based modeling, allow for connectivity to the existing ADMX cryostat, and allow for stackable cavity arrays. To accomplish these goals, I was provided with a Siemens NX license. Siemens NX is a high level CAD modeling program. It allows dimensions in a model to be linked to numbers in a spreadsheet. By using this feature, I was able to link all dimensions that may be frequently changed to a single Excel spreadsheet (Figure 1).

# of Cavities in Line (3 for 7, 5 for 19, 7 for 37)	Diameter of Cavity Chamber (mm)	Diameter of Cavity (mm)	Thickness of Cold Finger (in)	Width of Cold Figner (in)	Diameter of Bearing Hole (mm)	Hole Offset (mm)	Hole Diameter (in)	Antennea Diameter (mm)	Support Shaft Diameter (in)	Length of Long Shaft (mm)	Length of Short Shaft (mm)
3	426	120	0.25	4	5	24	0.375	5	0.25	122	56
5	426	70	0.25	4	5	14	0.375	5	0.25	65.2	27.6
7	426	43	0.25	4	5	8.6	0.375	5	0.25	40.85714286	15.42857143
Is Cavity Diameter Too Big?		Thickness of Cold Plates (mm)	Thickness of Caps (mm)		Tuning Rod Diamter (mm)	Tuning Rod Armature Length (mm)	Antennea Offset (mm)	Tuning Rod Length (mm)			
No		6.35	6.35		24	36	33.9411255	238			
No		6.35	6.35		14	21	19.79898987	138			
No		6.35	6.35		8.6	12.9	12.16223664	84			

Figure 1. Parameter Spreadsheet Screenshot

These dimensions control the diameter of the cavities, the number of cavities, the dimensions of the cavity supports, and several others. Each detector diameter only scans a very limited range of frequencies. It would be unacceptably expensive to completely redesign the detector to scan a new frequency range. By making all dimensions parameter based, a redesign is not necessary to change the frequency range.

The cavities must also be able to connect to the existing ADMX cryostat. Figure 2 shows the entire cavity assembly. The existing 1K mount plate connects to the cryostat. The cryostat allows the detector to reach 100mK as any heat will create signal noise and may taint the results of the experiment. Since a cryostat is a very expensive piece of equipment, it made sense to connect to the existing one rather than build a new one.

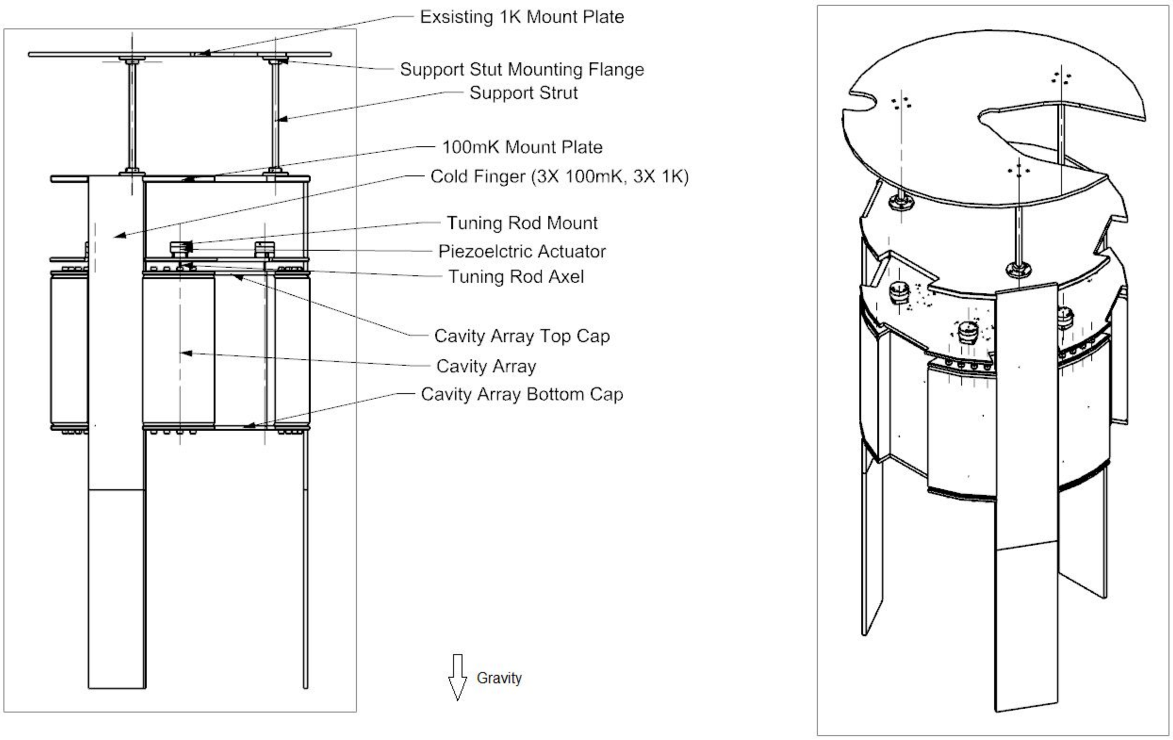
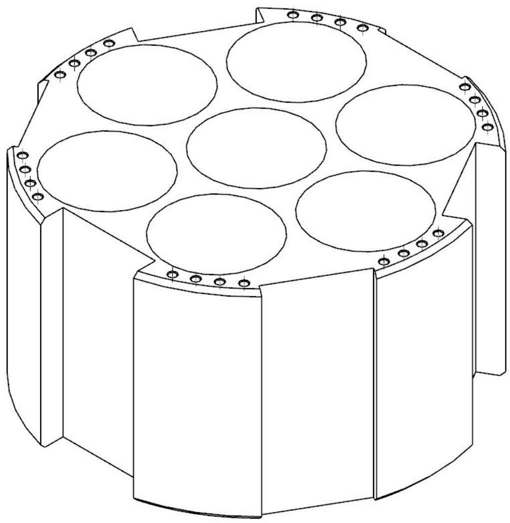


Figure 2. Detector Assembly (1K cold fingers not show, entire assembly 1.0m tall, 0.5m wide)

Finally, the cavity arrays must be stackable. That is, multiple arrays of cavities must be able to be stacked on top of each other. To do this, the cavities were designed into a cylinder as shown in Figure 3. We chose a hexagonal pattern because it maximizes the volume used for the cavities. Since each cavity must also have a rotating tuning rod (to calibrate its resonant frequency), a small piezoelectric motor must be mounted above the cavity. Since this motor generates a small amount of heat, it is connected to a warmer part of the cryostat and must be suspended over the cavity.



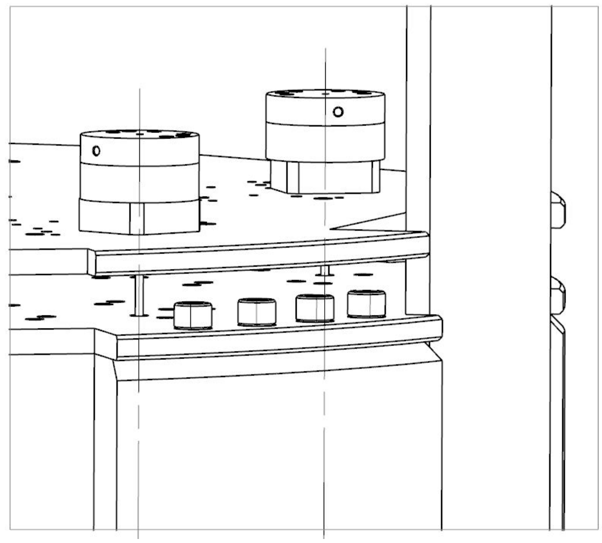


Figure 3. Cavity Array

Figure 4. Piezoelectric Mount

Figure 4 shows the motor and tuning rod assembly. Notice that the motor's mounting plate does not contact the cavity at all, but is held up by 3 struts. These struts connect to the warmer part of the cryostat directly. There are 3 more struts that connect the 100mK components to the 100mK Mount Plate.

Results

The three design requirements were satisfied, however several issues arose during the design. To fully tune the cavities, an antenna must be moved up and down inside each cavity. This linear motion accompanies the rotation of the tuning rods. To accomplish this motion, a linear piezoelectric actuator must be attached to the antennae. This creates a problem with cavity arrays with 19 or 37 cavities. At this point, the linear actuators and rotary actuators become too crowded. To solve this problem, I worked on implementing a system where four to six linear actuators moved all the antennas at once. We also looked into rotating all tuning rods at the same time, however we could not take that approach. Since each cavity is machined to slightly different dimensions, rotating all tuning rods together would result in a loss of precision that would be unacceptable. Figure 5 shows an image of the linear actuator solution. All dimensions for the solution are controlled by the excel interface. Figure 7 shows the tuning rod assembly. Each cavity has its own rotary assembly and the dimensions for each assembly are controlled through the excel interface. Figure 6 shows the tuning rod assemblies embedded in the cavities.

One of the most difficult problems we faced in designing the detector is thermal conduction between 1K and 100mK sections. Any place where parts at different temperatures touch can warm up the colder parts. These places include the tuning rod bearings and the three connectors between the 1K Mount Plate and the 100mK Mount Plate. In order to reduce these instances of heat transfer, materials were used that are bad conductors of heat, such as stainless steel, MACOR™, and aluminum based ceramics.

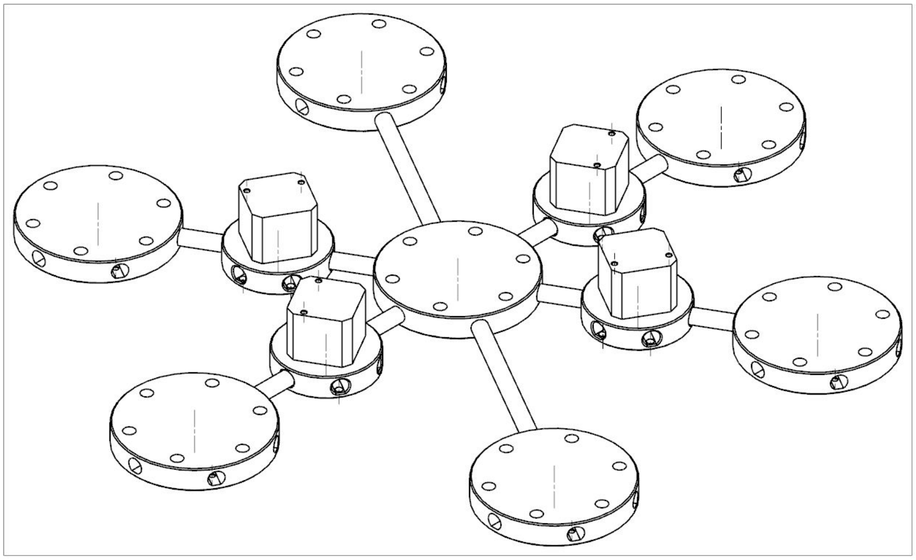


Figure 5. Antennae Assembly

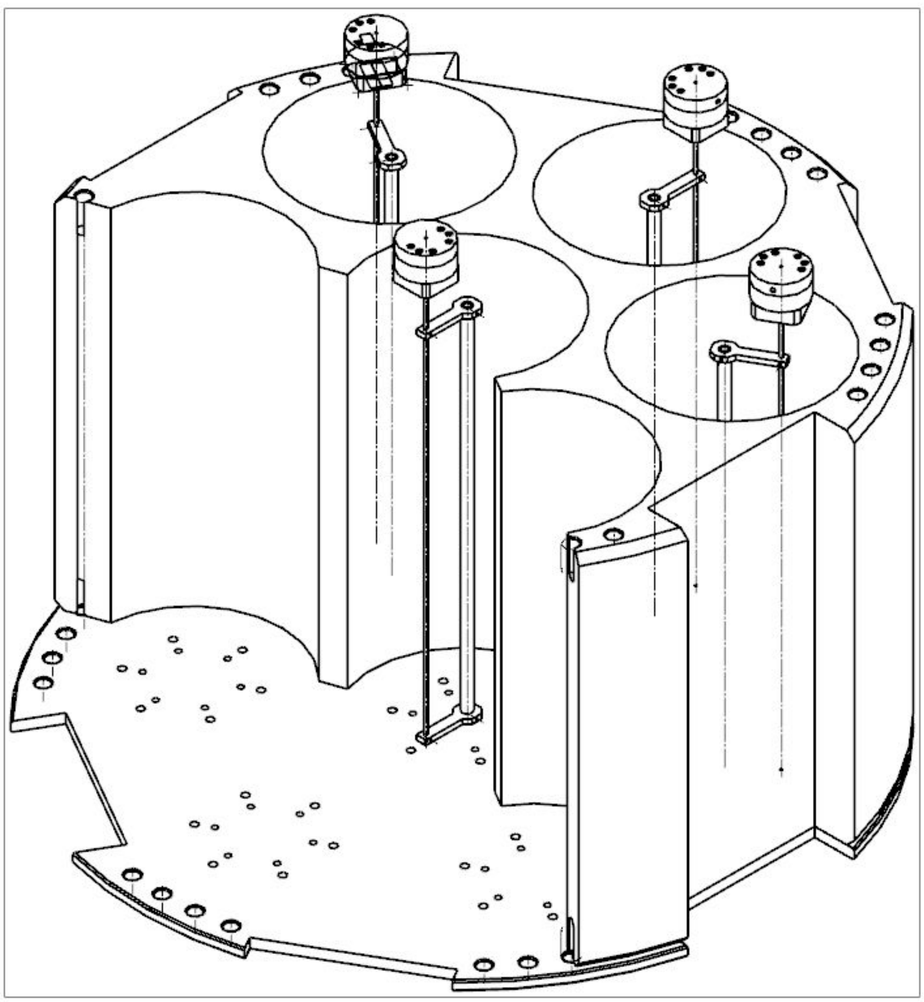


Figure 6. Embedded Tuning Rods

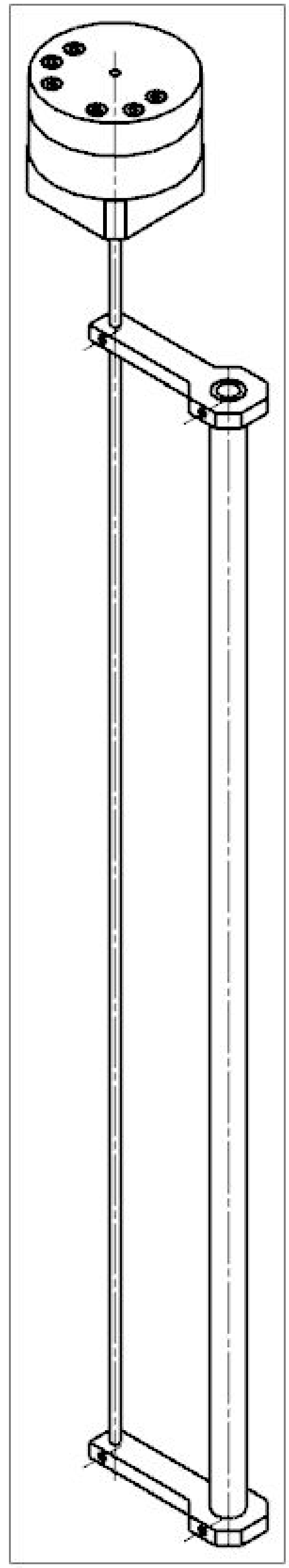


Figure 7. Tuning Rod Assembly

Conclusion

While we were able to solve the problems of thermal conduction, parameter based design, and connectivity to existing equipment, there are still two potential issues facing the project. The actuators and antennas all generate heat when electricity is run to them. This and the fact that the wires feeding to these devices come from outside the cryostat presents a thermal issue. The 100mK portion of the cryostat can only deal with a very small amount of heat (~80 micro watts). If too much heat is put into the cavities and they go above a certain temperature, the time between each tuning rod adjustment will increase to allow the detector to cool back down. Since the tuning rods are supposed to make extremely small movements once every second, any extra time in scanning could increase the scanning time of the entire frequency range by years. This issue may seem dire, but initial calculations have shown that heat generated by the actuators is nearly negligible as is the conduction across the wires. The next step is to construct a prototype to make sure all of our predictions are correct. If everything works out with the prototype, the full detectors will be built and the search for heavier axions will begin.

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