SSR1 Superconducting Resonator

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Abstract

The superconducting Single Spoke Resonator or (SSR1) was initially developed by Fermilab for the High Intensity Nutrino Source (HINS).[1] In addition, similar SSR1 resonators will be used for a future project called Project X Injector Experiment (PXIE) which consists in constructing a superconducting proton linear accelerator (linac).[2] Moreover, these SSR1 resonators have an operating frequency of 325 MHz and they are enclosed by a cryomodule at a temperature of 2K. [3] Furthermore, SSR1 resonators are assembled by many different components such as: The Frequency Tuner and Bellows, which have some unknown mechanical parameters that were obtained by the use of computerized analysis and experimental testing. The study of these components will help in unifying the SSR1 resonator to work as one, since it will demonstrate important properties and limitation of each part of the resonator. It will also permit scientists and engineers to establish the necessary boundaries and conditions that will contribute in the construction of superconducting linacs. Consequently, it will provide the field of particle physics with more powerful and sensitive tools that will help in the discovery of any new upcoming scientific frontiers. [2]

CONTENTS

I. INTRODUCTION

The SSR1 resonator main constituents are the superconducting cavity made from niobium and the helium vessel that is made from stainless steel 316L. Inside the niobium cavity is where the beam pipe and single spoke are located. The niobium cavity is enclosed by the helium vessel where the cryogens are pumped to maintain the required superconducting temperature. [4]

The Frequency Tuner consists of three main components: the actuation system, main arm and fulcrum. The actuation system is where the stepper motor and piezoelectric assembly is found. The stepper motor is used for coarse tuning and the piezoelectric assembly is used for fine tuning. The actuation system is mounted by threaded connections to the helium vessel. [6] The main arms consist of two stainless steel 316L arms with a probe in the middle that applies a force on the level tuner and elastically deforms a bellows. As a result, the helium vessel is deflected and maintains the desire resonating frequency. The fulcrum consists of two flexible joints that connect the end of the two main arms to the helium vessel as shown in FIG 1. Consequently, since the frequency tuner and the bellows interact with one another it is necessary to determine the bellows and main arm's stiffness. Moreover, this paper focuses on determining these parameters to establish a force to deformation ratio of the cavity and in the design of other components that allows the research and development of the SSR1 resonator to advance.

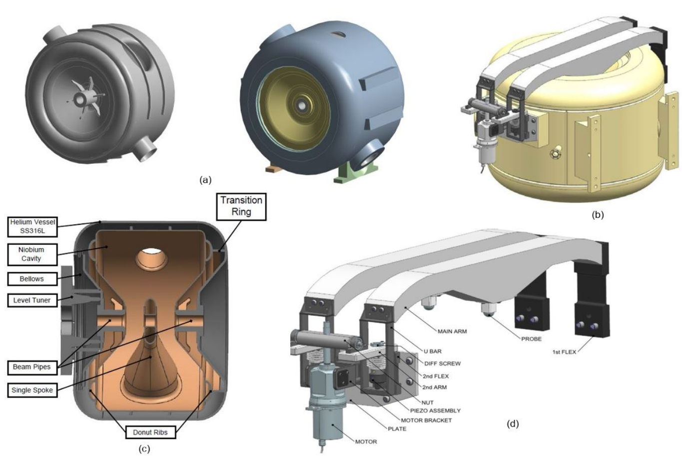

FIG. 1. (a) Niobium Cavity(Left) and Helium Cavity(Right). (b) Helium Vessel and Frequency Tuner. (c)Cross-Section of SSR1. (d)Frequency Tuner Parts. (See Appendix For Larger Image).

II. METHOD

The tools that where used for the Computer Aid Design (CAD) modeling and simulations were NX7.5 and ANSYS Workbench 14.5. In addition to computer related tools, a vacuum rough pump, ported vacuum table, dial indicators, pressure gauges, load cells and weights were used.

A. NX7.5

NX7.5 is a 3D and 2D CAD modeling software which was created by Siemens and it is also the current modeling software supported by Fermilab. Furthermore, this modeling software provides a user-friendly interface with many modeling features which gives the necessary tools to meet with any design specification.

B. ANSYS Workbench 14.5

ANSYS Workbench is a powerful tool that includes an extensive collection of Analysis System that permits simulation from different fields in engineering and physics. ANSYS Workbench works by importing a 3D model or creating inside ANSYS and then selecting a Analysis System according to the type of simulation. Moreover, the Analysis System that was used for the main arm is called Static Structural. Furthermore, this Analysis System allows one to choose, view and import materials.

III. MY CONTRIBUTION

A. Antenna Flange

The antenna flange is an important component for the welding process of the helium vessel since it detects any shrinkage that may occur by measuring the frequency and also measures the change in temperature inside the vessel, which indicates how much air must be let inside. The antenna flange is made of aluminum 6062 and has a 151.6mm diameter; it

FIG. 2. Antenna Flange mounted on the Helium Vessel.

also has sixteen 8.43mm diameter holes around the flange for bolted connection to the helium vessel. Furthermore, it also includes six 3mm diameter holes to place thermocouples inside and 1/4 inch National Pipe Thread (NPT) hole used to purge the vessel with argon. My contribution to the construction of the antenna flange was to make a 3D model and sketch with the desired specifications so it could be fabricated at the machine shop, as shown in FIG 2 and 3.

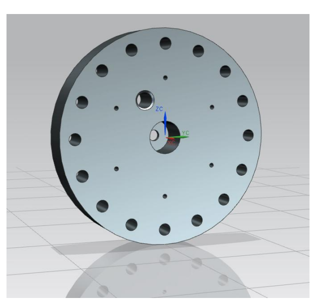

FIG. 3. Antenna Flange 3D model made with NX7.5. (See Appendix For Sketch).

B. Main Arm

The main arm's stiffness was calculated by simulating a linear elastic analysis in ANSYS Workbench. This analysis consisted in measuring the directional deformation the arm undergoes when a force is applied. Additionally, since the main arm deformed in the elastic region, Hooke's Law was used to calculate the stiffness.

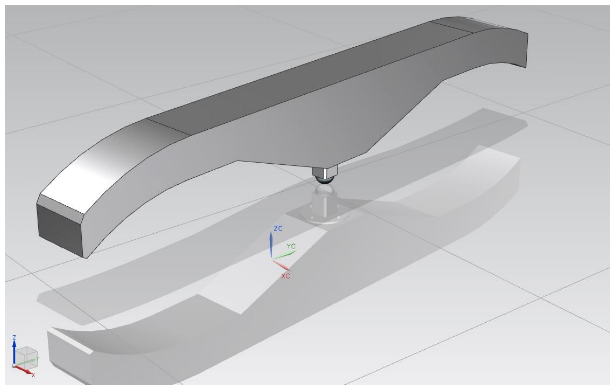

FIG. 4. Main Arm 3D CAD Model

In order to simulate the most realistic situation as possible, the main arm was constrained with 0 displacement in the y-axis and x-axis.

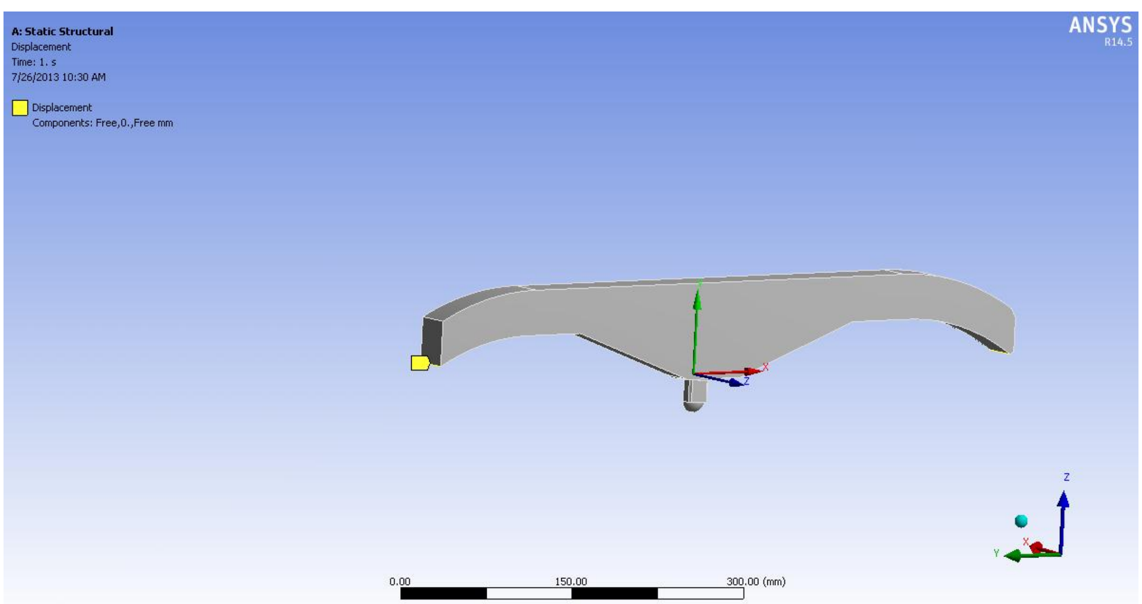

FIG. 5. Constrain in the y-direction

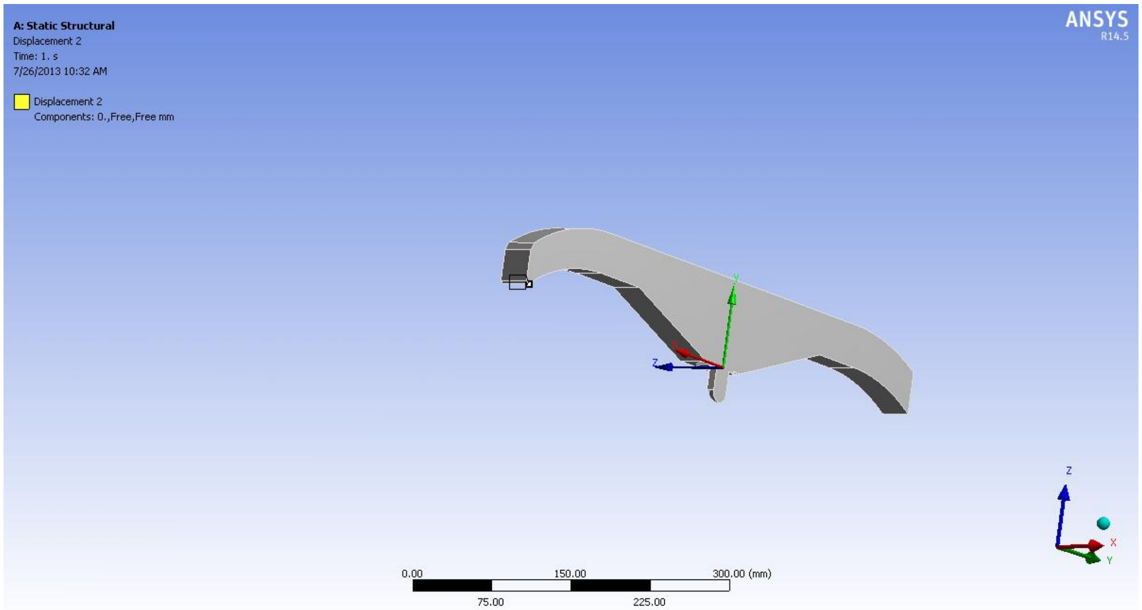

FIG. 6. Constrain in the x-axis

The use of symmetry when performing static simulation has many benefits, because the model becomes smaller resulting in faster solutions and more stable since the symmetry plane eliminates one degree of freedom (DOF). [5] In the case of the main arm's stiffness simulation only one symmetry plane was created reducing the model by half as shown in FIG 7.

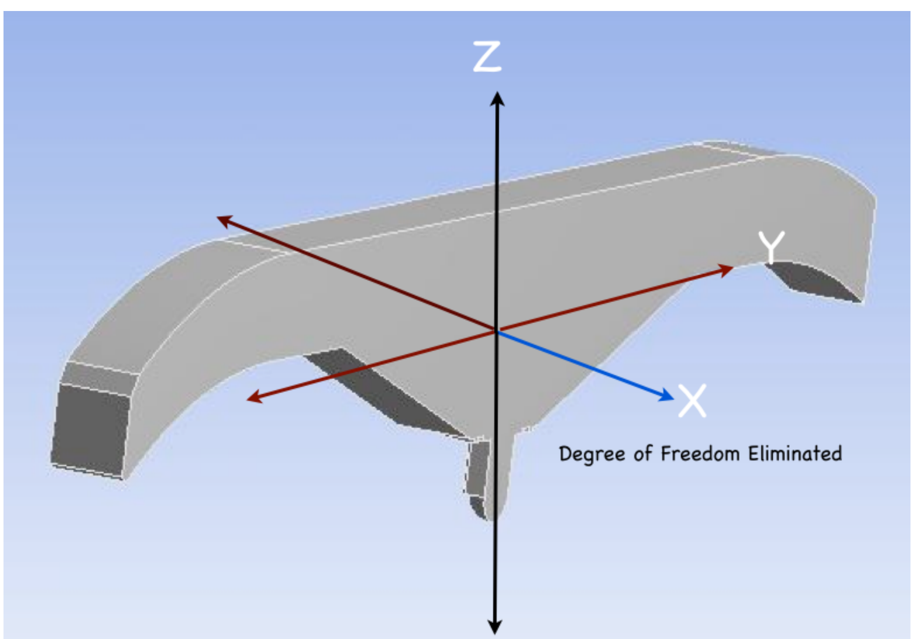

FIG. 7. Symmetry plane of the main arm eliminating one DOF.

The magnitude of the force that was used for this simulation was 200N. Moreover, since the symmetry plane acts like a mirror, FIG 8 illustrates a magnitude of 100N in the y direction using the symmetry plane or z direction model plane.

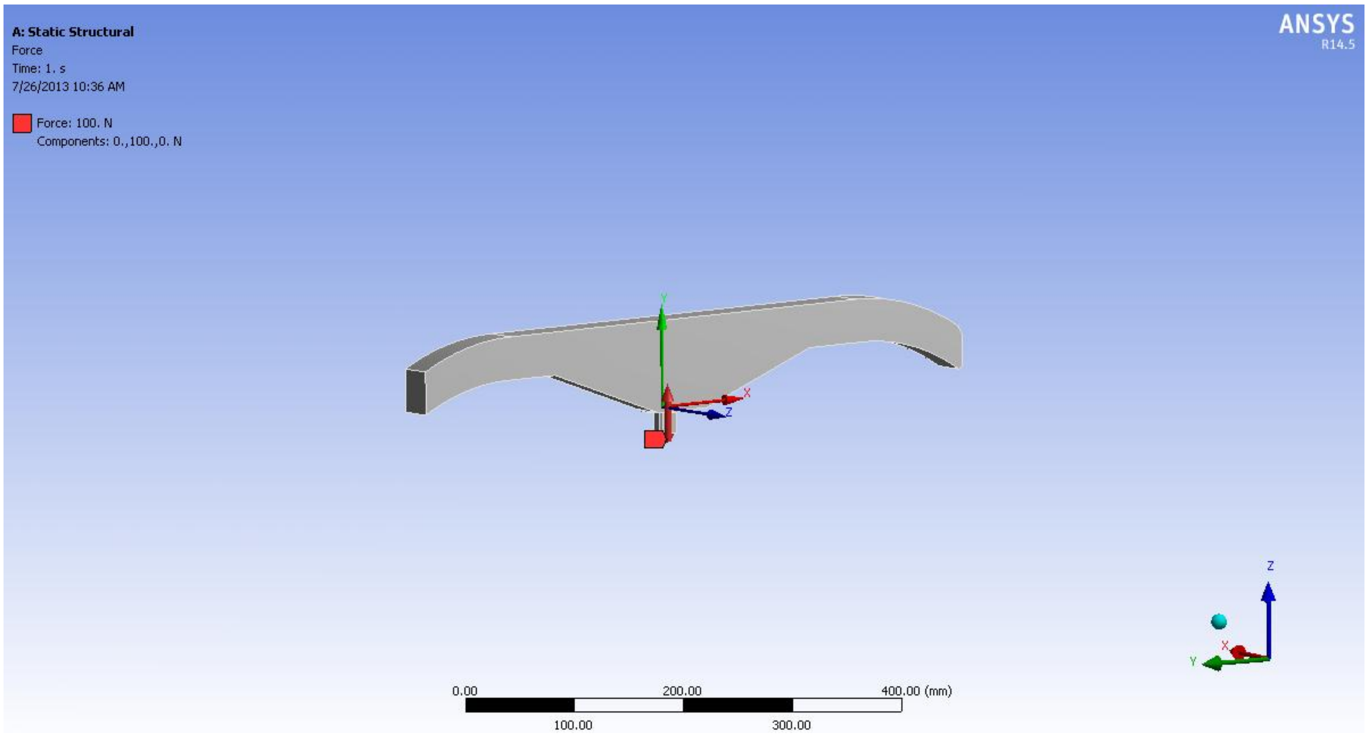

FIG. 8. 100N Boundary Condition

An important process in any 3D model simulation is the mesh selection processes. This process is done by making a convergence study of how values change according to the mesh refinement. The convergence study consists of plotting results vs number of elements graph and selecting the number of elements that correspond to the converging result value as shown in FIG 9 encircled in red.

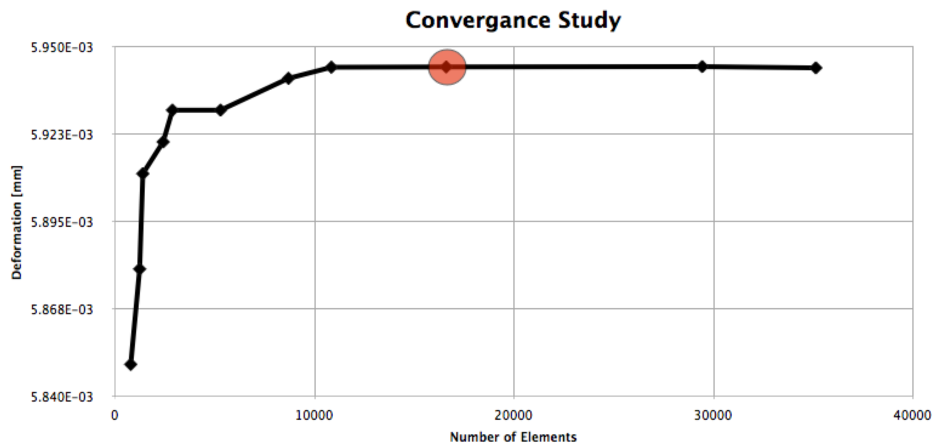

FIG. 9. Convergence Study Plot of Deformation of The Main Arm vs. Number of Elements

The value that is encircled in FIG 9 corresponds to a number of elements equal to 16,588. This number of elements correspond to the mesh shown in FIG 10.

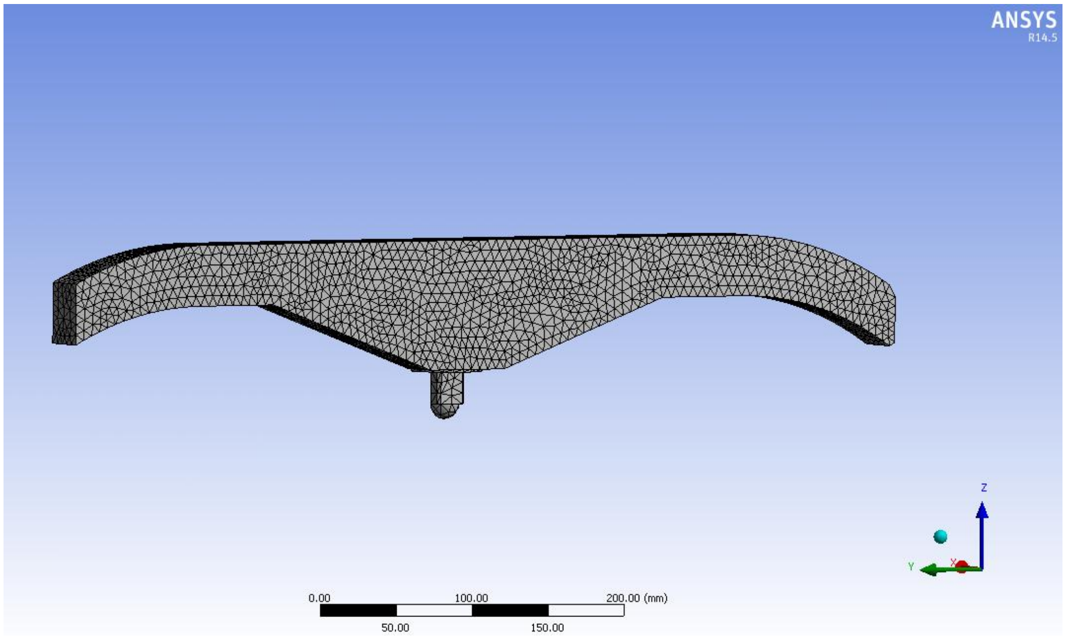

FIG. 10. Mesh Illustration

Using the selected mesh, the simulation yielded a directional deformation value of 0.0059436mm. The stiffness was aquired by applying Hooke's Law:

$$k = \frac{F}{x}$$

Let $F = 200N$ and $x = 0.0059436mm$, the stiffness of the Main Arm equals to $k = 33.6\frac{kN}{mm}$.

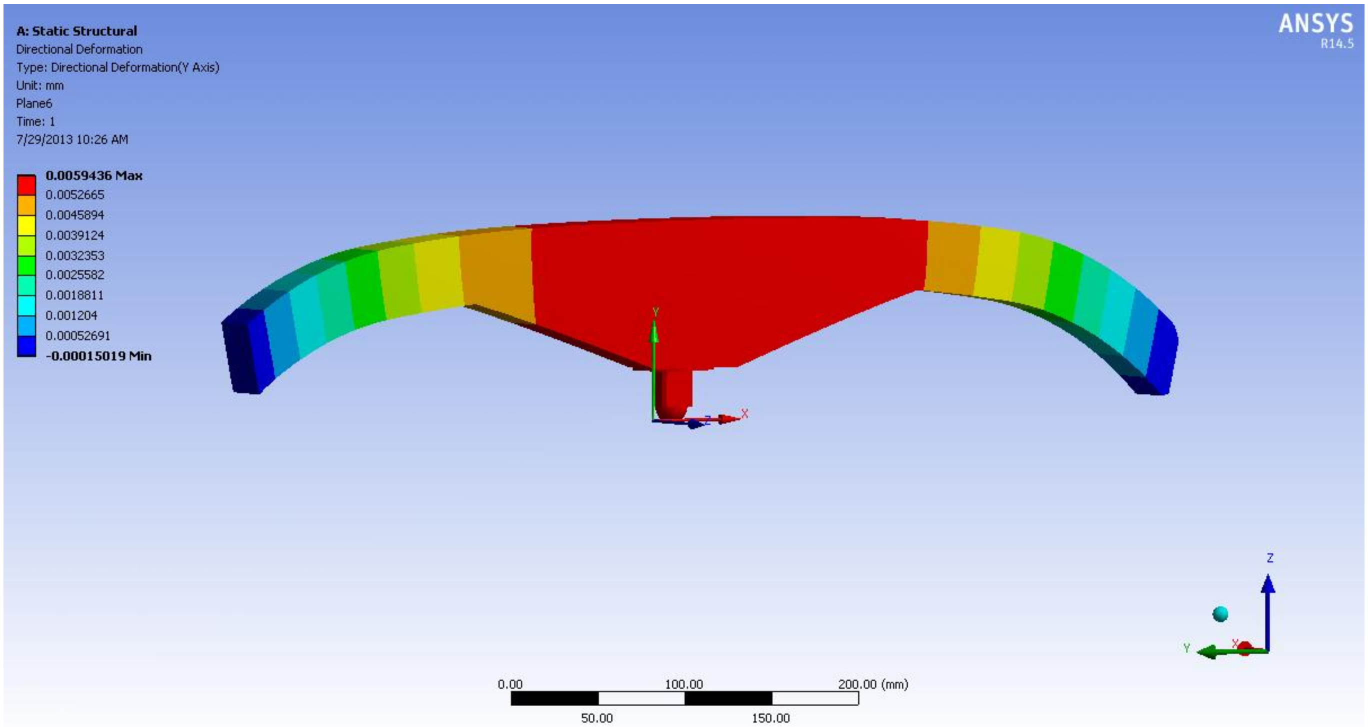

FIG. 11. Directional Deformation Simulation

C. Bellows Experiment

This experiment consisted in placing weights on the top plate of the bellows and measuring, with dial indicators, the deformation that occurs in the vertical direction. In addition, in this experiment the weights that were used were approximately 7.9 kilograms. Furthermore, since the deformation and force acting on the top plate are known, the bellows' stiffness can be calculated.

In order to get the most accurate results, the bellows was glued to a table and the top plate. In addition, the dial indicators were glued as well to avoid any shifting and false measurements as shown in FIG 12 and 13.

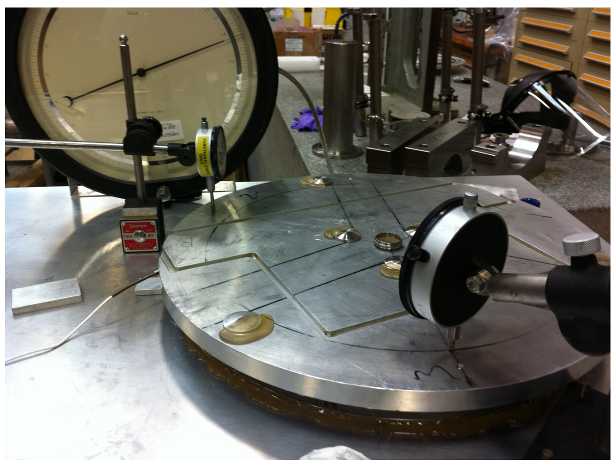

FIG. 12. Setup of Dial Indicators

FIG. 13. Bellow Between Table and Top Plate

The weights are going to be added 3 at a time until a total of 9 weights are placed in the top plate as shown in FIG 14 and 15. The deformation of the bellows will be measured each time the weights are added. Once the weights are added they will be removed 3 at a time, taking measurements in between.

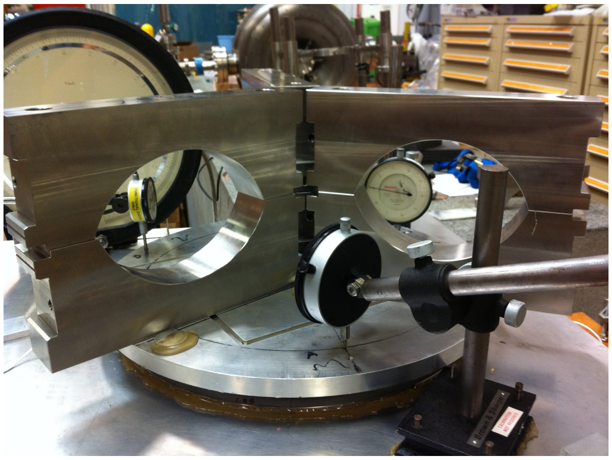

FIG. 14. Six Blocks on The Top Plate

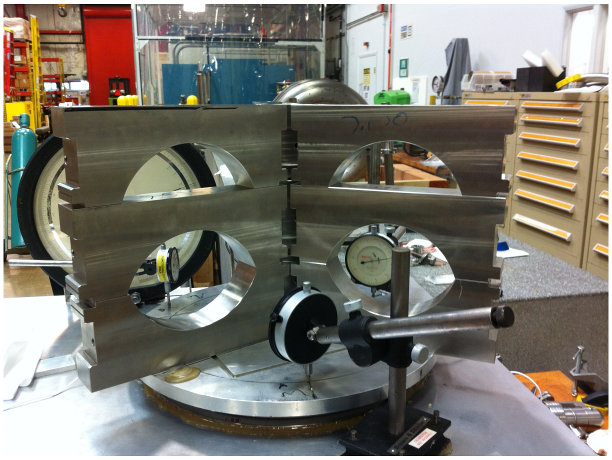

FIG. 15. Nine Blocks on The Top Plate

The results from this experiment are shown in FIG 16.

Block Qty	Force	Dial 1		Dial 2		Dial 3	
	[N]	[inch]	[mm]	[inch]	[mm]	[inch]	[mm]
0	0	0	0.000	0	0.000	0	0.000
3	223.67	0.0172	0.437	0.0155	0.394	0.01569	0.399
6	447.16	0.0333	0.846	0.0309	0.785	0.03092	0.785
9	670.65	0.0585	1.486	0.0452	1.148	0.04658	1.183
6	447.16	0.03321	0.844	0.031	0.787	0.0315	0.800
3	223.67	0.01651	0.419	0.0159	0.404	0.01601	0.407
0	0	0.0001	0.003	0	0.000	0.0001	0.003
3	223.67	0.0171	0.434	0.0151	0.384	0.00151	0.038
6	447.16	0.033	0.838	0.0309	0.785	0.0308	0.782
9	670.65	0.05831	1.481	0.0458	1.163	0.0468	1.189
6	447.16	0.03415	0.867	0.031	0.787	0.0315	0.800
3	223.67	0.017	0.432	0.016	0.406	0.0161	0.409
0	447.16	0.00009	0.002	0	0.000	0.00019	0.005
3	223.67	0.01734	0.440	0.0155	0.394	0.01508	0.383
6	447.16	0.0334	0.848	0.0304	0.772	0.0304	0.772
9	670.65	0.05936	1.508	0.045	1.143	0.05733	1.456
6	447.16	0.0345	0.876	0.031	0.787	0.03512	0.892
3	223.67	0.1696	4.308	0.0159	0.404	0.0159	0.404
0	447.16	0.00049	0.012	0	0.000	0.0001	0.003

FIG. 16. 9 Experiment Results

The stiffness of the bellows was estimated by creating three Deformation vs. Force plots with the data acquired and taking the inverse of the slope of the linear treadline. Moreover, Hooke's law can mathematically be expressed as $f(x) = mx + b$. Let $f(x) = d$, $x = F$, $m = \frac{1}{k}$ and $b = 0$. Hooke's law can be written as: $d = \frac{1}{k}F$ where d is the displacement, F is the force, $\frac{1}{k}$ is the slope of the treadline and k is the stiffness.

The first graph was made with all the data measured from the experiment as seen in FIG 17.

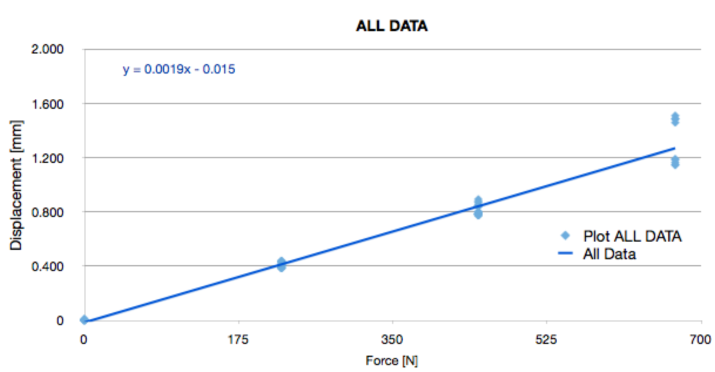

FIG. 17. All Data Deformation vs. Force Plot

The plot that is illustrated in FIG 18 was made using the maximum deformation data shown in TABLE I to determine the minimum stiffness.

Force [N]	Displacement [mm]
0	0
223.67	0.440
447.16	0.892
670.65	1.508

TABLE I. Maximum Displacement Data

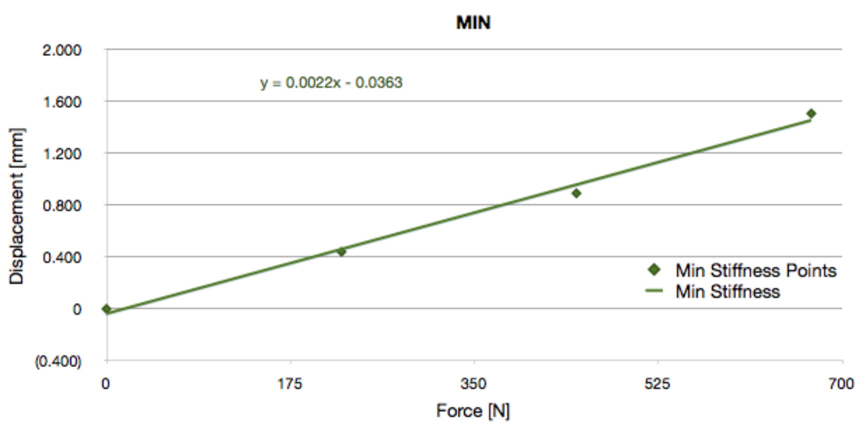

FIG. 18. Maximum Deformation vs. Force Plot

The plot that is illustrated in FIG 19 was made using the minimum deformation data shown in TABLE II to determine the maximum stiffness.

Force [N]	Displacement [mm]
0	0
223.67	0.383
447.16	0.777
670.65	1.143

TABLE II. Maximum Displacement Data

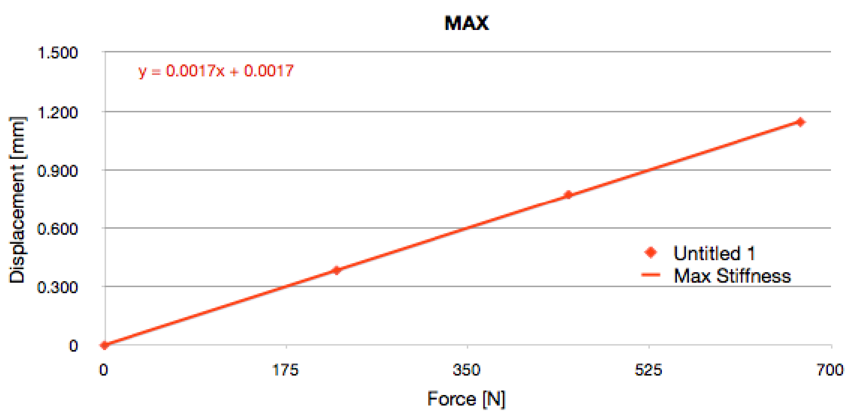

FIG. 19. Minimum Deformation vs. Force Plot

The Results of the stiffness are shown TABLE III.

Minimum Stiffness	$454.5\frac{N}{mm}$
All Data Stiffness	$526.3\frac{N}{mm}$
Maximum Stiffness	$588.2\frac{N}{mm}$

TABLE III. Maximum Displacement Data

Using the maximum and minimum stiffness and by doing a simple mathematical calculation: $\frac{k_{MAX}-k_{MIN}}{2} = 67\frac{N}{mm}$. The bellows estimated stiffness can be calculated: $k_{est} = 526.4 \pm 67\frac{N}{mm}$.

D. Tuner Test Stand Prototype

The idea of the Tuner Test Stand Prototype is to design a cost effective and easy to make stand for the Frequency Tuner. The main purpose of this design is to have a place to test and mount the Tuner when not mounted on the helium vessel. In addition, in the case the Tuner would need modifications it would be easier to perform any modifications in the Tuner Test Stand than inside the cryomodule.

The Tuner Test Stand design consists in the principal and end plate where the Actuation System and the Fulcrum will be mounted by bolted connections. The frame will be assemble by 1"x1" square tubes made from stainless steel or aluminum. The first prototype of the Tuner Test Stand is illustrated in FIG 20.

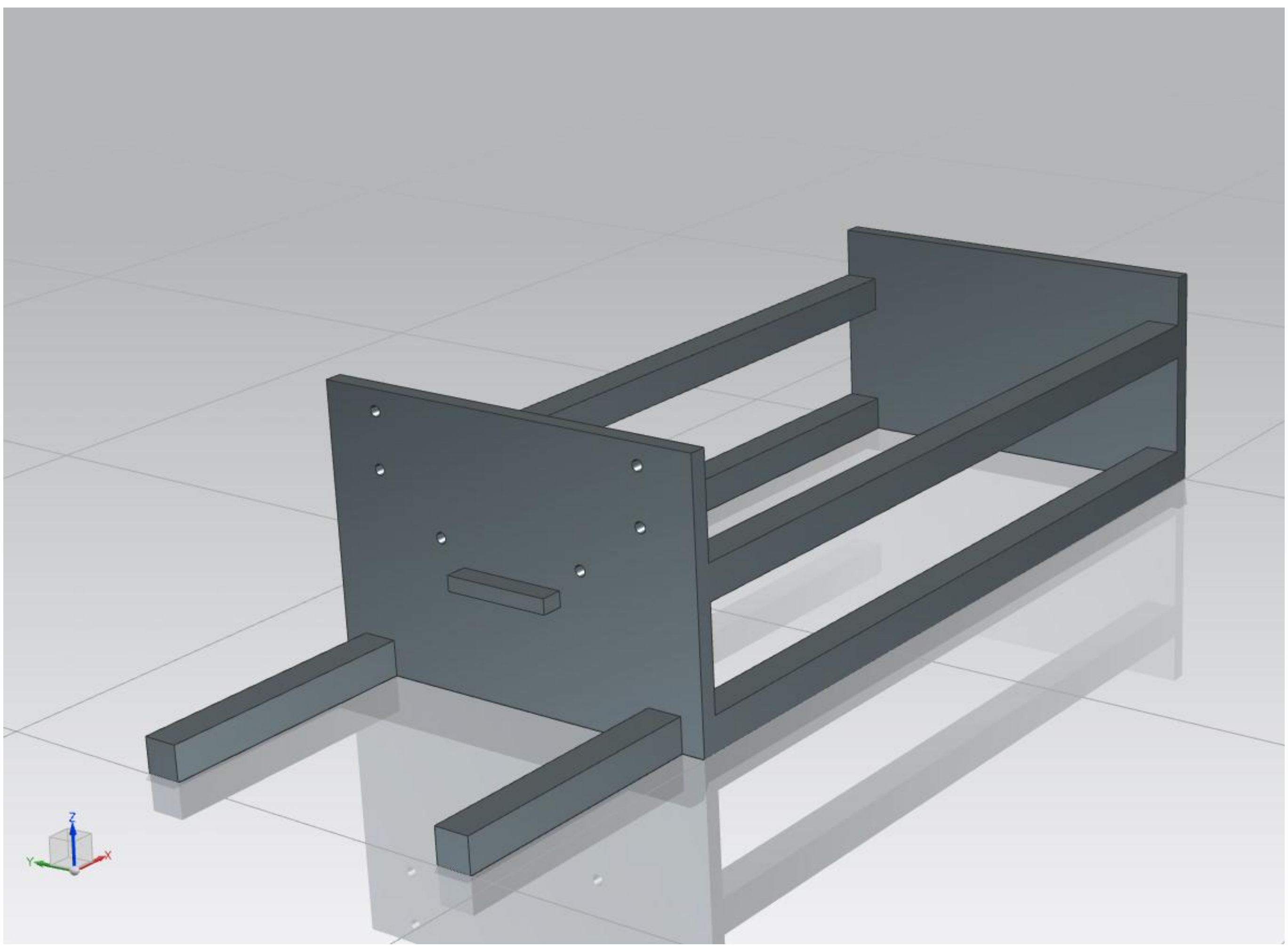

FIG. 20. First Prototype of The Tuner Test Stand

FIG 21 and 22 show an assembly of the Frequency Tuner and the Tuner Test Stand Prototype from different angles.

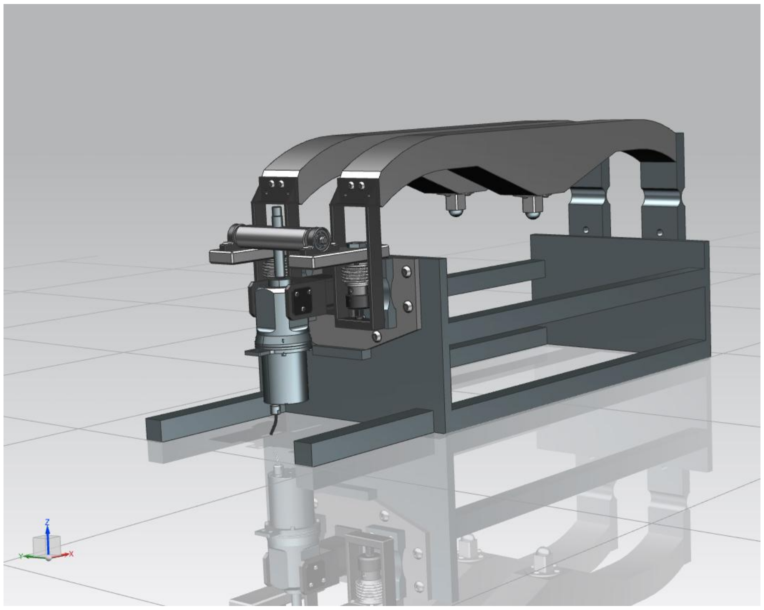

FIG. 21. Assembly of Frequency Tuner Mounted on The Tuner Stand 1

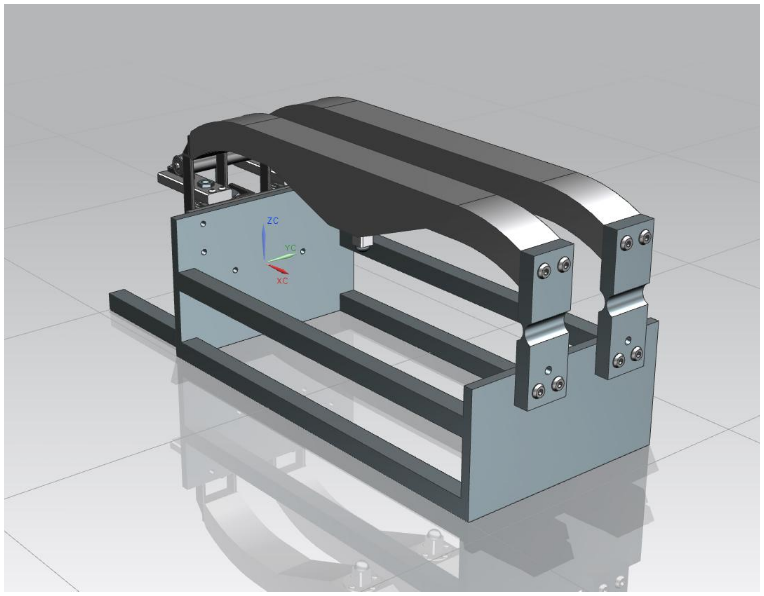

FIG. 22. Assembly of Frequency Tuner Mounted on The Tuner Stand 2

IV. CONCLUSION & FUTURE WORK

As for my summer's work and contribution, I feel confident with the results of the main arm's simulation, the design of the Tuner Test Stand and that the Antenna Flange sketch was done correctly since it was created in machine shop and used for the welding process of the helium vessel. On the other hand, although the blows experiment had a wide margin of difference to determine a stiffness with accuracy, the data demonstrated that the experiment is effective because the results could be model with a linear regression with a coefficient of determination close to 1.

As for future work, the bellows' stiffness experiment can be improved by repeating the experiment and obtaining more data that will help to pin point the stiffness of the bellows with more accuracy. In addition, other experiments to calculate the stiffness and effective area of the bellows were done but there was no time to analyze the results. These experiments consisted in decreasing the pressure inside the bellows below the atmospheric pressure and measuring the vertical displacement and the force using: dial indicators, two load cells, a pored vacuum table and a vacuum rough pump. Furthermore, 3 additional load cells were ordered to make a more stable setup for future tests. As for the Tuner Stand Prototype, is in the idea phase but it will definitely be a necessary addition to aid in the research and development of the SSR1 Resonators in the future.

V. ACKNOWLEDGEMENT

I would like to thank Leonardo Ristori, my supervisor, for the excellent advice throughout my Internship. I would like to thank Donato Passarelli for allowing me to work with him, making me part of the team at Technical Division. I would like to thank Derek Plant for sharing his vast knowledge in hands-on applications and particle accelerators. I would like to thank the entire SIST committee for giving me this amazing opportunity to grow as a professional. Last but not least, I would also like to thank Fermilab National Accelerator Laboratory and The Department of Energy for funding this amazing program.

VI. APPENDIX

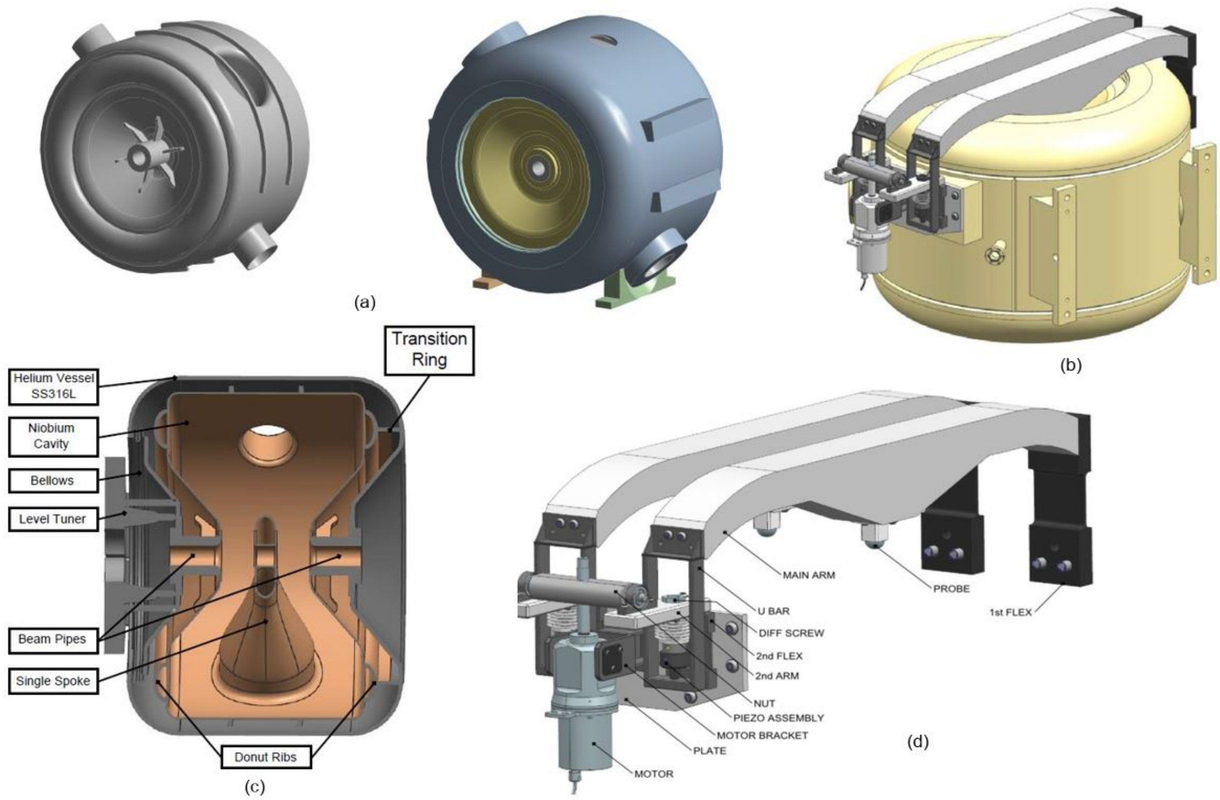

FIG. 23. (a) Niobium Cavity(Left) and Helium Cavity(Right). (b) Helium Vessel and Frequency Tuner. (c)Cross-Section of SSR1. (d)Frequency Tuner Parts. (See Appendix For Larger Image).

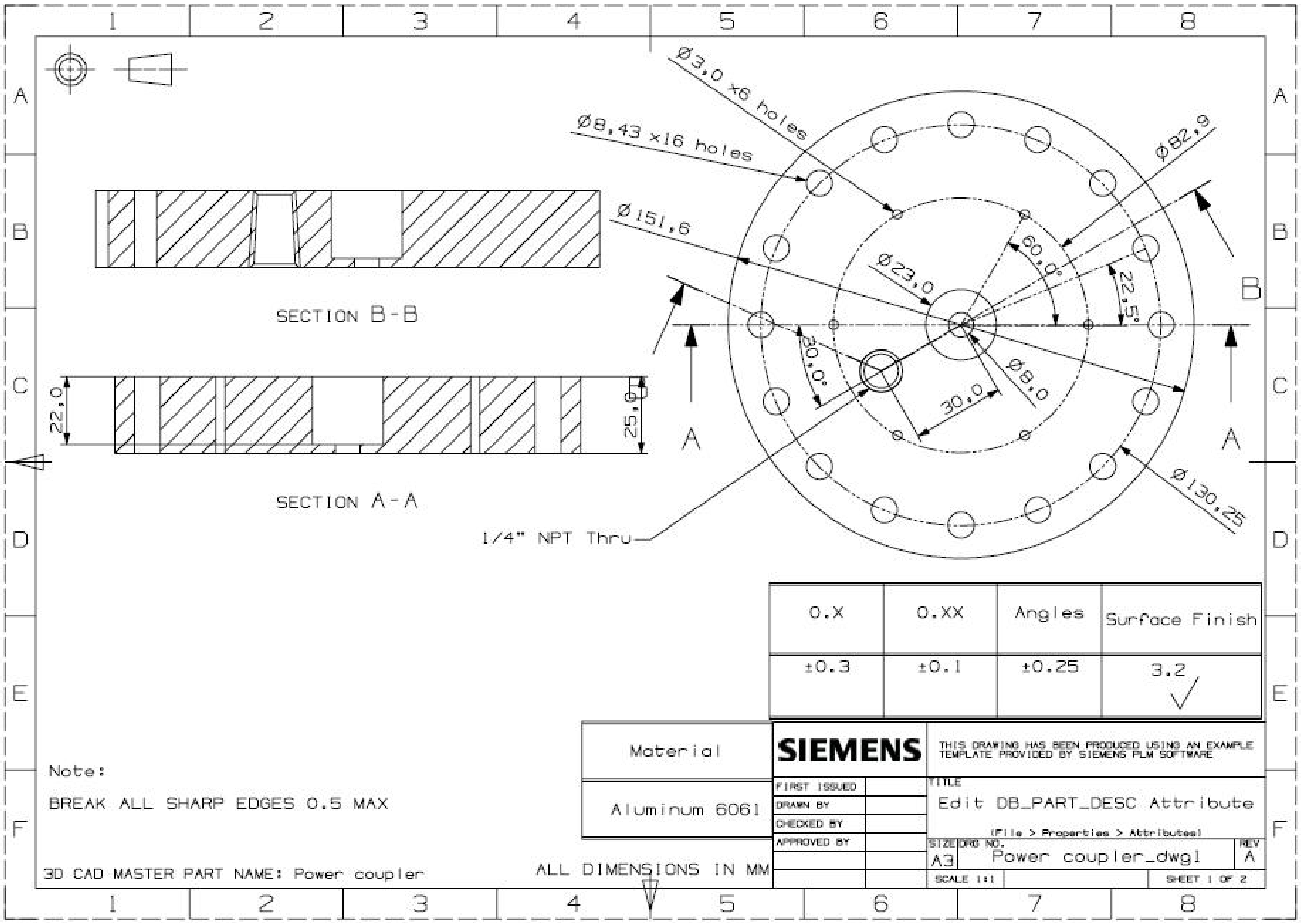

FIG. 24. Antenna Flange Sketch made with NX7.5.

[1] A. Carrion. *SSR1 Cavities for PXIE,* 2012.

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