Mechanical Resonances of SRF Cavities: Setting resonance for maximum efficiency

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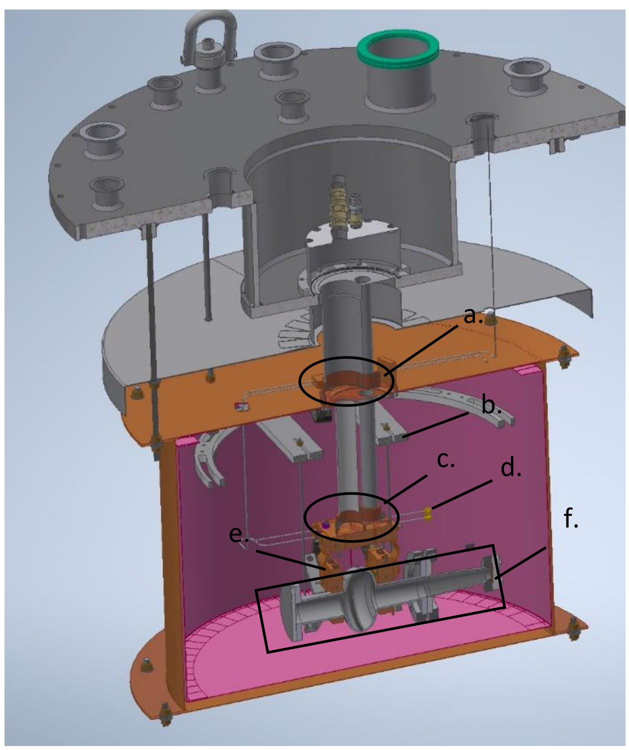
Abstract:

Superconducting radio frequency (SRF) technology is applied to numerous accelerators. Contrary to previous copper cavities, superconductivity has much smaller requirements in energy leading it to be much more efficient. With the development of a new material of SRF, Nb_3Sn, it has opened a possibility of using a cryocooler instead of liquid helium to keep the cavity at a temperature of around 4K. The problem, however, is that with the use of the cryocooler it is impossible not to have vibrations occurring throughout the assembly. With vibrations occurring within the overall assembly, these may affect the cavity which can lead to creating mechanical resonance. Our objective of the project is to analyze the cavity by setting certain mechanical boundary conditions and inspect the frequencies where the cavity can sustain its overall shape and operate in a stable fashion.



Overall image of the SRF testing assembly. The cavity and the beam tubes can be seen near the bottom of the accelerator (f.).

Introduction:

Every object within the real world has a natural frequency of vibration. When a force is applied at a frequency that matches the object's resonant frequency, resonance occurs. An example of this in everyday life can be found easily such as the pendulum, or in larger scale a bridge collapsing due to the cadence of people walking on the bridge matching its natural frequency. As the accelerator is made of many components, a modal analysis is necessary to accurately predict the mechanical properties of the accelerator. As can be seen from above, the accelerator consists of the first stage cold head (a.), the assembly support ring and crossbars (b.), the second stage cold head (c.), the RF power cables (d.), the copper cooling assembly (e.) and the cavity and the beam tubes (f.). The first stage cold head and the second stage cold head are the parts that cools the parts of the assembly, with the second stage cold head focused in keeping the cavity assembly cooled down to 2K. The assembly support ring and crossbars are used to withstand weight of the cavity assembly. The RF power cables are normally connected to power couplers to supply the assembly with energy. The copper cooling assembly is of copper braids and beam clamps, which transfers the heat from the cavity assembly to the second stage cold head to keep the cavity assembly at around 4K. To prevent severe vibrational interaction within the accelerator, our project focused on modal analysis of the cavity and beam tubes. Modal analysis is simply put, an analysis to inspect the frequencies and the characteristics of an object in mechanical situations. We applied the use of a program called ANSYS to obtain these calculations.

Theory:

Within the accelerator, as the SRF cavity is the most sensitive to vibrations, the sole focus of our simulations was on the cavity, beam tubes and the aluminum cradles. By setting supports, and temperature-specific material properties to the given parts it would be possible to simulate the condition to anticipate the modal shape of the cavity. Using modal analysis can lead to an understanding of the mechanical vibrations that the cavity can withstand before the overall shape of the cavity is distorted. Within ANSYS, multiple analysis can be applied to a given geometry. For the purpose of this project, static structural and modal analysis were used. By accessing the mechanical toolset of the structure, it will make it possible to apply mechanical traits on the given geometry. For this project, the cavity and beam tubes were to undergo meshing and to be broken down into elements to enable numerical simulation. Finer meshing of the geometry makes it possible to achieve a more accurate simulation and analysis. After creating boundary conditions that will be similar to the actual structure of the cavity and beam tubes in real life, solving for the simulation will lead to a dynamic view of the deformation of the geometry as well as yield the resonance frequencies.

Procedure:

The basic idea of this project was that by applying boundary conditions on the cavity and beam tubes in the form of supports and loads, it would be possible to simulate a condition in which the cavity would be in when the accelerators are operated. To achieve these results, analysis of several models was undertaken. These were just the cavity, the cavity with the beam tubes, and the cavity, the beam tubes with cradles. The cavity and the beam tubes were set to have a thermal condition of 4K, which is roughly the temperature the structure will be at when operating, and with the materials to be of niobium. Niobium was added to the list of materials within the engineering database with Young's modulus of 1.23 E+11 Pa and Poisson's ratio of 0.38 to the isometric elasticity. To more specifically control the area where the beam tubes were to be in touch with the cradles, they were gone through a process of meshing called body sizing to an element size of 3.00mm. To simulate a condition where the cradles will be in place, two areas within the beam tubes were selected to create contact regions along with the gravitational and thermal boundary conditions. By adding a gravitational boundary condition, it made it possible to simulate the gravity on Earth to be applied to the overall structure, with thermal boundary condition of 4K. By selecting the target and contact regions it was possible to create an environment which assumes that there is contact on the beam tubes.

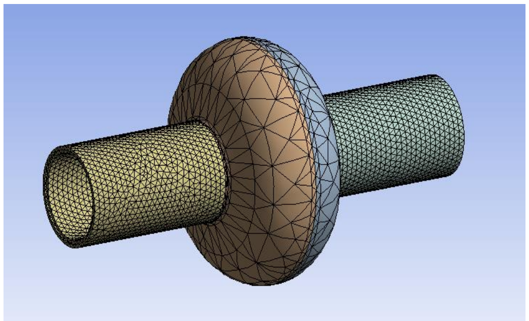
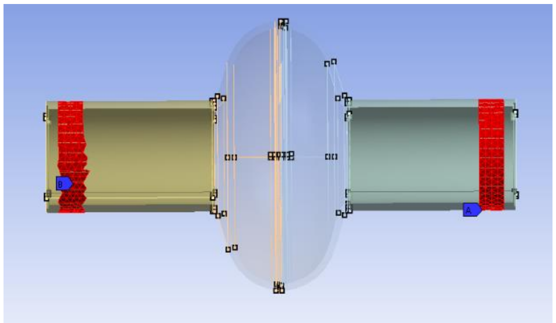


Image of the cavity and beam tubes before modal analysis. The beam tubes have a denser mesh, due to body sizing the elements to the size of 3.00 mm



Area of red on the beam tubes are the contact regions between the tubes and the cradles, necessary for simulating the cradles

Results:

An initial analysis of just the cavity was made to help gain understanding of the overall analysis done through ANSYS. Without specific boundary conditions such as gravity or thermal conditions, an analysis of the cavity with two edges restricted to a fixed state was done. Within the actual assembly, the outer edges of the cavity were not going to be in such a fixed state, and this analysis was mostly used as a reference for better understanding ANSYS.

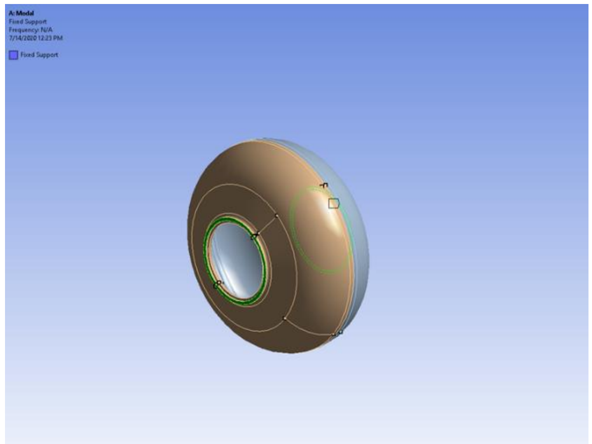
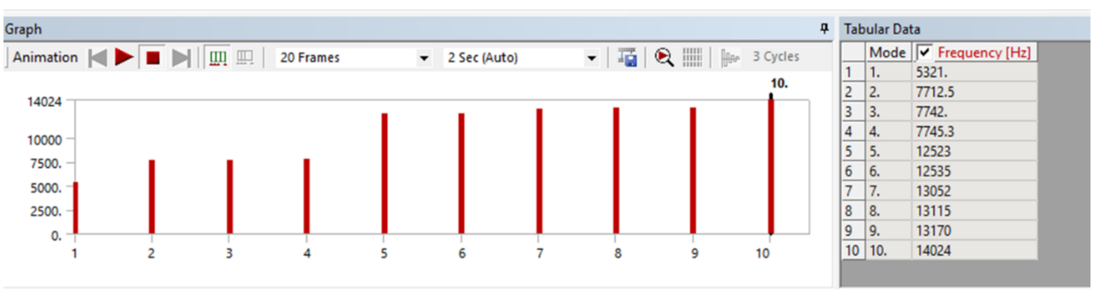


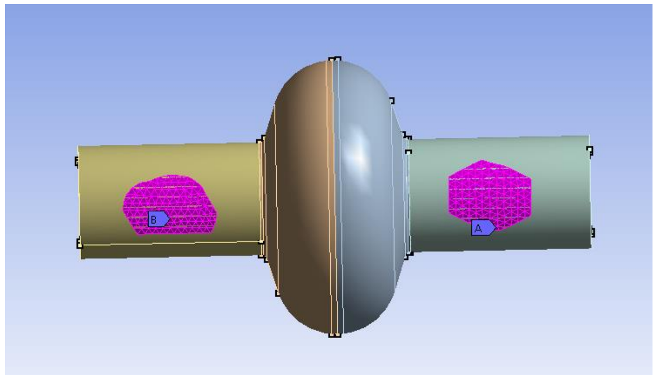
Figure of just the cavity, with the
green edges being in a fixed state.



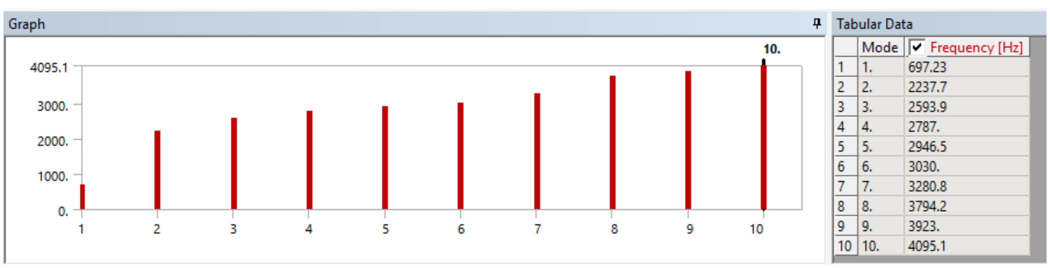
	Mode	Frequency [Hz]
1	1.	5321.
2	2.	7712.5
3	3.	7742.
4	4.	7745.3
5	5.	12523
6	6.	12535
7	7.	13052
8	8.	13115
9	9.	13170
10	10.	14024

Frequencies recorded for just the
cavity with edges in a fixed state

A more complex analysis was done where a fixed support on the bottom of the beam tubes was applied, with gravitational and thermal boundary conditions added. This led to a more realistic simulation of the cavity and the beam tubes but was a bit off from the actual model. The location of the contact region was different to that of where the actual cradles were to be, as well as the fact that the beam tubes were not going to be in a state of being welded to the cradle. The frequency where the cavity maintained its shape was at 697.23 Hz, with movement as though the cavity and the beam tubes were rocking back and forth while the bottom seemed as though it was fixed to a position.

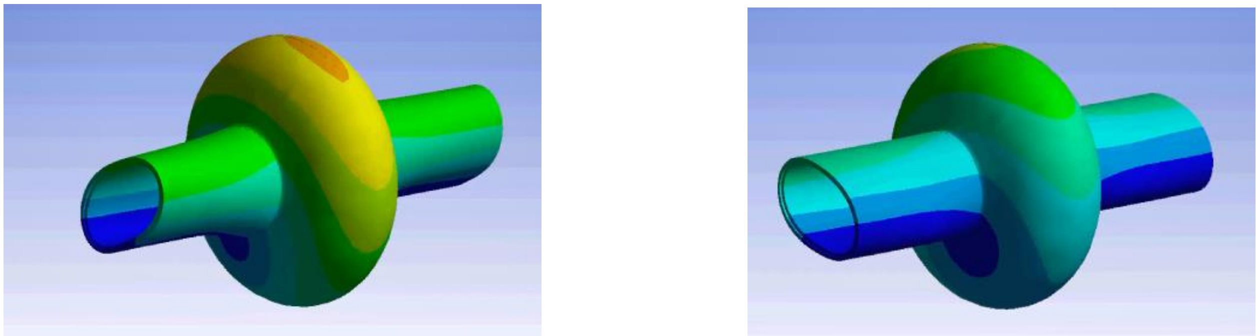


Highlighted area of assumed contact regions on the beam tubes. The area in purple was set to have a fixed support, to simulate the force of the cradle on the beam tubes.



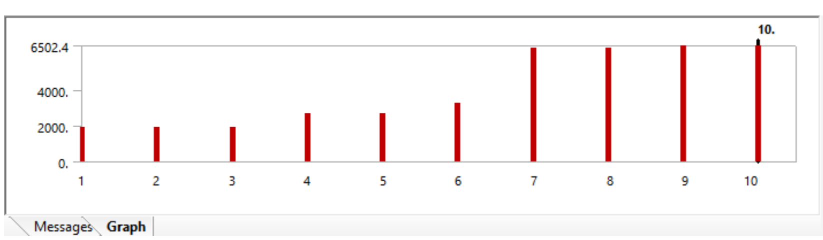
	Mode	Frequency [Hz]
1	1.	697.23
2	2.	2237.7
3	3.	2593.9
4	4.	2787.
5	5.	2946.5
6	6.	3030.
7	7.	3280.8
8	8.	3794.2
9	9.	3923.
10	10.	4095.1

Recorded frequencies of cavity with simulation of contact regions as fixed supports. The cavity maintained shape only at 697.23 Hz, with huge distortions in larger frequencies



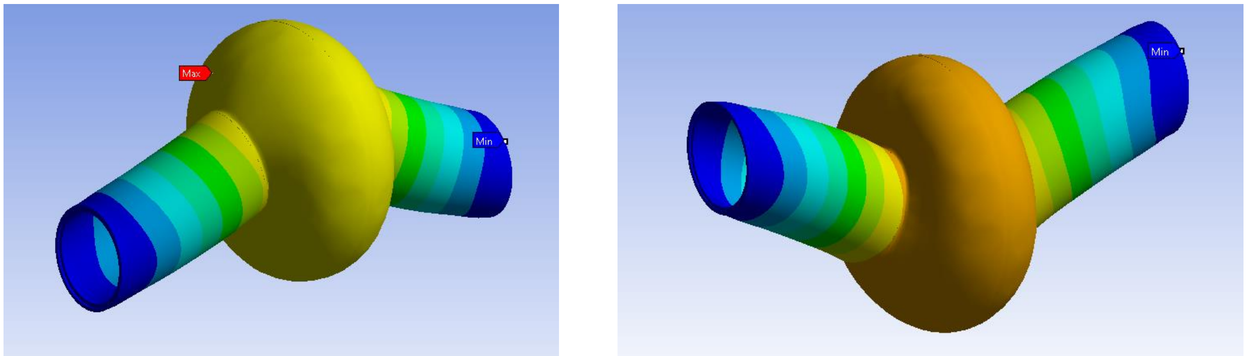
Modal analysis of cavity with fixed contact region at 697.23 Hz. The cavity and the beam tubes take a form of rocking back and forth

For the most realistic modal analysis, contact regions were manually created to resemble the regions where the cradles were to be in place and were put in a no-separation condition which allowed the analysis to act as though the beam tubes were on the cradles not as though they were welded to them. Through modal analysis, three frequencies were inspected where the cavity along with the beam tubes successfully managed to maintain its overall shape. Resulting with 1926.2 Hz, 1927.2 Hz and 1958.4 Hz the modal actions at 1926.2 Hz and 1927.2 Hz resembled each other similarly only with a difference of direction in which the cavity took motion in. As the motion was the same but only in different directions, this likely explains why the frequencies have only a difference of 1 Hz. Around 1958.4 Hz, the cavity seemed to take an expanding motion in the vertical direction.

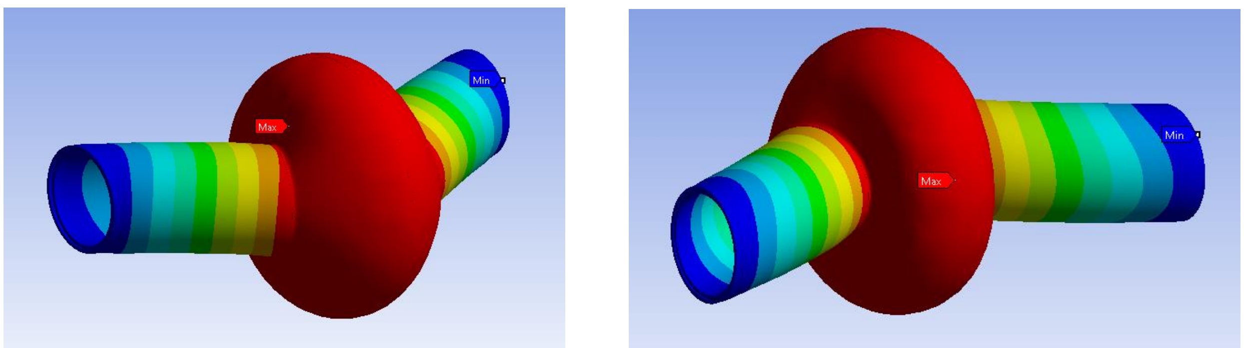


	Mode	Frequency [Hz]
1	1.	1926.2
2	2.	1927.2
3	3.	1958.4
4	4.	2677.2
5	5.	2686.3
6	6.	3279.7
7	7.	6392.9
8	8.	6398.8
9	9.	6497.3
10	10.	6502.4

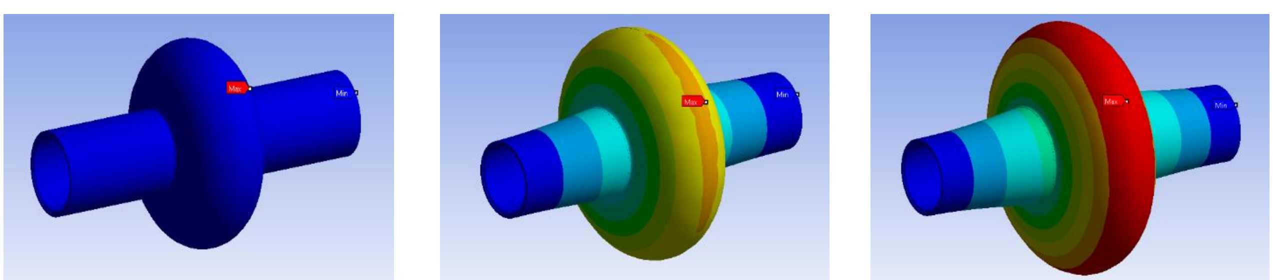
Frequency results from analyzing cavity and beam tubes with simulation of contact regions



Modal shape of cavity at 1926.2 Hz



Modal shape of cavity at 1927.2 Hz



Modal shape of cavity at 1958.4 Hz

Conclusion:

Through modal analysis, it can be noted that as the resonance frequency remains below 1958.4 Hz, the cavity and the beam tubes can withstand the vibrations without significantly harming the efficiency while the accelerator is in operation. However, though theoretically adding contact regions on the bottom of the beam tubes may seem effective, it is worth noting that without any geometry that is in actual contact ANSYS may not have been putting in the effect of force that will act upon the beam tubes. Possible solutions to have a more accurate simulation would be to implicate the use of point mass or create a geometry that resembles the cradles.

Point mass can be effective to simulate the effect of the cradles for they can designate areas where a specific amount of force will act upon. Point mass is a tool which allows simulation of force on a specific remote point which must be the face of a certain geometry. By selecting a face of a geometry and creating a remote point under the model tab, it is possible to designate the specific area as a remote point where the force will be acted upon. However, to do so it will require dividing up the beam tubes to two separate parts to create a geometry where there will be contact with the cradles.

Another way to accurately simulate the cradles, it may be more effective to create a new geometry of the cradles to more accurately simulate the force that will act upon the tubes. By creating a new geometry, it is possible to create more accurate boundary conditions. The possible boundary conditions would be to have the cradles fixed into a specific location and to consist of a material of aluminum.

References:

H. Padamsee , RF superconductivity 2010 Science, Technology and Applications

Acknowledgement:

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