MECHANICAL DESIGN OF 56 MHZ SUPERCONDUCTING RF CAVITY FOR RHIC COLLIDER*

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Abstract

A 56 MHz Superconducting RF Cavity operating at 4.4K is being constructed for the RHIC collider. This cavity is a quarter wave resonator with beam transmission along the centerline. This cavity will increase collision luminosity by providing a large longitudinal bucket for stored bunches of RHIC ion beam. The major components of this assembly are the niobium cavity with the mechanical tuner, its titanium helium vessel and vacuum cryostat, the support system, and the ports for HOM and fundamental dampers. The cavity and its helium vessel must meet equivalent safety with the ASME pressure vessel code and it must not be sensitive to frequency shift due to pressure fluctuations from the helium supply system. Frequency tuning achieved by a two stage mechanical tuner is required to meet performance parameters. This tuner mechanism pushes and pulls the tuning plate in the gap of niobium cavity. The tuner mechanism has two separate drive systems to provide both coarse and fine tuning capabilities. This paper discusses the design detail and how the design requirements are met.

INTRODUCTION

The function of the 56 MHz SRF cavity is to provide a large longitudinal bucket for stored bunches of the RHIC ion beam. The high voltage in the cavity provides a larger bucket which will increase the luminosity (collision rate) in RHIC. To provide a high gap voltage over 2 MV, this cavity is designed as a superconducting cavity using high RRR niobium. The shape of the 56 MHz SRF is a quarter wave resonator which has a 56 MHz frequency (Fig. 1). This shape has been optimized to have peak electric field with the magnetic field as low as possible. This cavity has a very high Q and is beam driven. In normal operation it is detuned a few hundred hertz from beam driven frequency. Thus its operating frequency controls the voltage on the gap and must be very accurate. The accuracy is in the 1.0 Hz range.

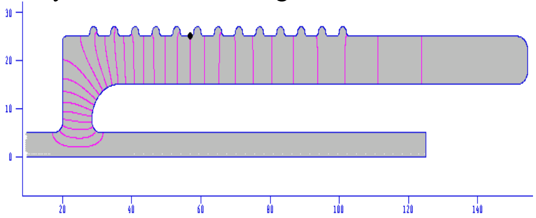

Figure 1: Shape of 56 MHz cavity.

DESIGN FEATURES OF SRF CAVITY

The shape of the 56 MHz RF Cavity is a re-entrant cylinder with the beam pipe along the cavity axis. Cooling of this superconducting cavity is by 20 psi liquid helium. Precise resonant frequency is critical for RHIC operation. With these conditions there are four structural design requirements needed to implement this cavity vessel design. 1. Prevent multipacting. 2. Low helium pressure sensitivity and Lorentz detuning. 3. Cavity vessel has to meet the ASME Pressure vessel code requirements for safety. 4. Provide precision mechanical tuning for frequency control. Fig. 2 shows the Niobium/Titanium Vessel.

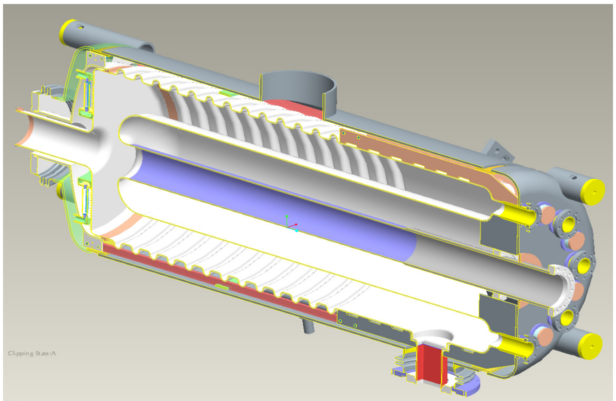

Figure 2: Niobium/Helium Cavity Vessel.

Mechanical tuning is achieved by pushing or pulling the flat part of the cavity to change the distance of the gap. The tuning sensitivity of the gap distance is 17 KHz/mm. Corrugation in the outer cylinder wall is to prevent multipacting. One large port in the lower part of the cylinder is used for the penetration of fundamental damper. On the right end of the cavity there are 16 small pipe structures equally spaced on the end plate. Eight pipes are penetration ports used for power couplers, HOM dampers, and other instrumentation. The other eight pipes are structural ports used for reinforcement and support for the RF cavity when welded to helium vessel. The material of the cavity is high RRR grade pure niobium. Typical Thickness of the cavity is 3 mm (.118 in).

PRESSURE SENSITIVITY

The SRF cavity is cooled to 4.4 K by liquid helium bath. The operating pressure of the liquid helium is 20 psi. When filled to the operating liquid helium level, there is pressure head in the helium bath. Also, during operation the heat transfer between SRF cavity and liquid

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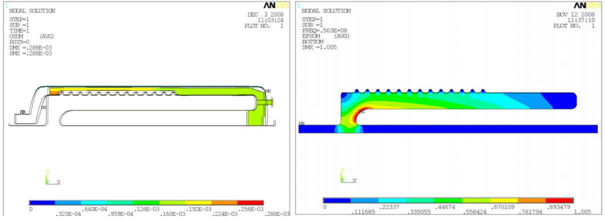
helium will generate boiling and convective flow in the helium bath around the SRF vessel. This will induce small pressure fluctuation in the SRF cavity. The range of the pressure fluctuation is assumed to be less than 1.0 mbar. The resonance frequency of the SRF is affected by its shape. When helium pressure increases the shape will be reduced. This will lead to the change of resonance frequency. It is important to know the frequency sensitivity of the SRF cavity to pressure fluctuation. The design goal of sensitivity is less than 1 Hz per 1 mbar. A Finite Element code, ANSYS Multiphysics, was used to analyze the effect of the pressure sensitivity. First, a structure model was built to calculate the deformation of the cavity under helium pressure.



Deformed Shape Frequency and E-field

Figure 3: Model for sensitivity analysis.

Then the deformed shape of the cavity was remodeled to perform Electro-Magnetic calculation to calculate resonance frequency (Fig. 3). The pressure sensitivity is calculated by the net effect of frequency change due to pressure fluctuation. The calculated value is .282 Hz per mbar meets the design requirement.

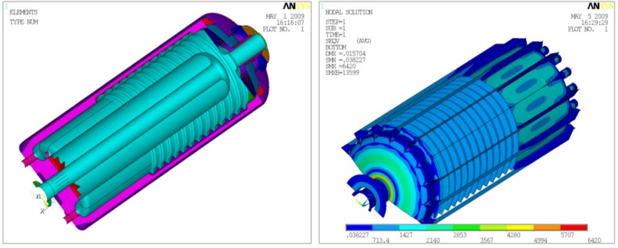
MULTIPACTING

The corrugation in the cylinder wall is to prevent multipacting. Structurally, the corrugation behaves as a flexible bellows. To prevent the corrugation from compressing under helium pressure and changing the cavity properties, 16 equally spaced stiffeners are placed along the length of the cylinder. These stiffeners are extended to the end plate of the cavity and welded to the penetration ports and the center beam pipe. These stiffeners reinforce the shape of the cavity and reduce both lateral and axial deformation of the RF cavity when it is pressurized. These stiffeners help to reduce the pressure sensitivity of the cavity frequency.

ASME CODE COMPLIANCE

According to ASME Code section VIII, division 2, “Design by Analysis”, there are 4 failure modes that this cavity vessel needed to be checked for compliance. 1. Protection against plastic collapse. (Evaluated by membrane and bending stresses). 2. Protection against local failure. (Evaluated by principle stresses). 3. Protection against collapse from buckling. 4. Protection against failure from cyclic loading, including ratcheting assessment.

To check the pressure vessel code compliance, an integral ANSYS model was built to calculate stress level in all critical components. Shell element was used to calculate primary membrane and local bending stresses. There are 3 loading conditions applied in the structure; 1. 20 psi pressure from liquid helium. 2. 760 lb weight from the vessel structure. 3. Temperature of whole structure is cooled to 4.4^{o}K. From the calculated results, all membrane and bending stresses anywhere in the structure were below allowable limits. Fig. 4 shows the integral ANSYS model and a typical stress plot of the cavity vessel.



Integral cavity vessel Model Typical stress plot

Figure 4: Model for ASME code calculation.

Critical buckling was checked by Eigen value buckling method. Both main cylinder and crown head (Fig. 5) are within allowable limits. With less than 1000 times of predicted operation cycle, fatigue is not a concern in this cavity. Overall, this cavity vessel structure meets the ASME pressure vessel code requirements and will achieve equivalent safety.

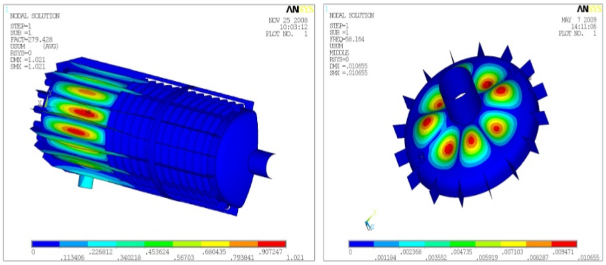


Figure 5: Buckling mode shape of cavity.

MECHANICAL TUNING

The mechanical tuning is achieved by pushing or pulling the upper flat part of the cavity. To keep this relatively flexible tuning plate free from vacuum or helium pressure, a separate torispherical head is added over the tuner plate in the upper part of the RF cavity. This makes the tuning plate an internal structure. Even though this plate is attached to the pressure vessel, this plate is not exposed to the helium or vacuum pressure. Fig. 6 shows the complete model of the tuner mechanism and the schematic view of the two stage tuner layout. Followings are the parameters of the tuner:

Tuning plate (Gap) Sensitivity: 17 KHz/mm
Tuner Type: Two stages, simple lever arm mechanism.
First stage is in the inside of cryostat (cold).
Second stage is in the outside of cryostat (warm).
Mechanical leverage: Total: 24.88
  First stage leverage: 3.77
  Second Stage leverage: 6.60
Tuning Deflection/force in the tuner linkage:

First stage: 1.5 mm/190 lb
Second Stage: 37.3 mm/7.6 lb
Coarse Tuning: By Stepping-Servo motor
Tuning Range: 25.5 KHz.
Tuning resolution: .038 Hz/step
Max. Tuning speed: 3.4 KHz/sec
Fast Tuning: By Piezo Drive.
Tuning Range: 60 Hz
Tuning Resolution: .06 Hz/volt

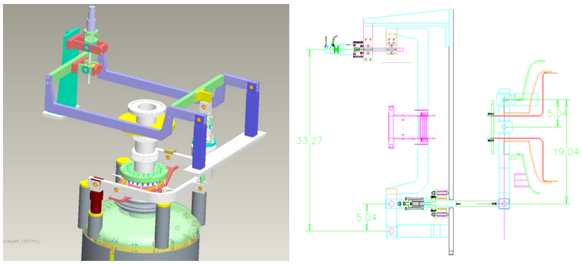


Figure 6: Tuner model and schematic.

SUPPORT AND CRYOSTAT

The cold superconducting cavity is supported by a room temperature space frame through pairs of radial and longitudinal nitronic rods. The space frame is supported by the vacuum chamber (Fig. 7).

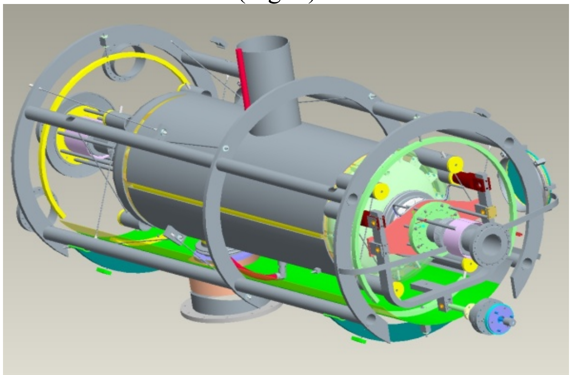


Figure 7: Support frame and Nitronic rods.

Weight support and radial position of the cavity against beam center is maintained by 4 pairs of criss-crossing nitronic rods in each end of the cavity. Longitudinal position and tuning force support are provided by 4 pairs of nitronic rods equally spaced around the helium vessel. The stiffness of these longitudinal rods is more than 30 times higher than tuning plate stiffness. These long and low conductivity nitronic rods reduce heat leaks from room temperature to the cold body. The symmetrical arranged nitronic rods, when cold, will each shrink and rotate the same amount to keep the cavity self centered. The radiation shield sitting inside of the space frame around the cold cavity is made of aluminium plate with welded extruded tube for cooling. The cooling of the shield is by flow of boil off helium gas. To prevent flow induced vibration in the gas helium line from affecting cavity, the heat shield is supported directly by the vacuum chamber without touching any part of the space frame. There will be two blankets of multi-layer super insulation Mylar (MLI) placed in both sides of the radiation heat shield to further reduce the radiation heat loss from room temperature. Outside of the heat shield, there are two layers of magnetic shields to shield any external stray magnetic field from leaking into the cavity. One layer is attached in the inside of the space frame. The other layer is attached in the outside of the space frame. Together these two layers of room temperature Amumetal will provide a total attenuation rate of 213 to cut down any magnetic leakage field to acceptable level (Fig. 8).

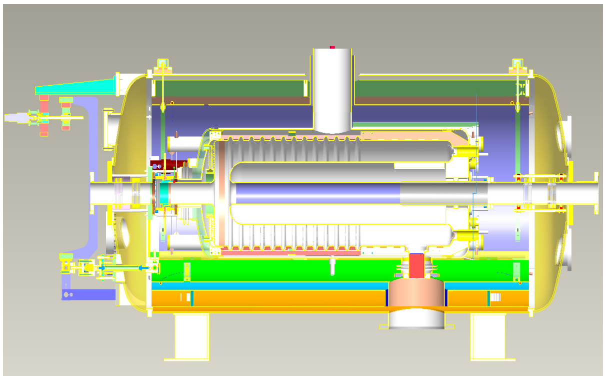


Figure 8: Cross section view of 56 MHz Cryostat.

CONCLUSION

The physics requirements and design concerns of the 56 MHz cavity makes the mechanical design a challenging task. The concept to place the tuner plate inside the cavity vessel as an internal structure together with stiffener bars around the cavity to protect the corrugations and reinforce the cavity have solved three difficulties; 1. Protect corrugation used to eliminate multipacting. 2. Reduce frequency sensitivity due to pressure fluctuation. 3. Meet ASME pressure vessel code requirements. The external tuner also makes the longitudinal cavity support system critical. By using symmetrical nitronic rods and non-frictional preload springs the cavity is well supported to resist tuner force. The design of cavity/helium vessel is complete and is being fabricated. The cryostat design is moving along in the final stage of integration and will be fabricated soon.

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