STUDY OF HIGHER ORDER MODES IN HIGH CURRENT MULTICELL SRF CAVITIES

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Abstract

The electron cooling project for RHIC luminosity upgrade and future projects such as eRHIC (electron-ion collider) demand cavities operating at high average current and high bunch charge in CW energy recovery mode. This paper describes the investigation of Higher Order Modes (HOMs) in such a cavity. This work is part of an ongoing effort to develop a 5-cell superconducting cavity for such high current and high bunch charge energy-recovery superconducting linac. The frequency of the cavity is 703.75 MHz with an iris of 17cm and two ferrite absorbers for HOM damping. The main focus of this paper is to identify and investigate possible trapped HOM modes that might result in multibunch instabilities. Detailed MAFIA calculations were performed using the e-module for different end cell geometries. Results from these calculations will be presented. Beam breakup results using TDBBU due to dipole HOMs will also be presented. A beam breakup threshold of above 1.8 A was calculated.

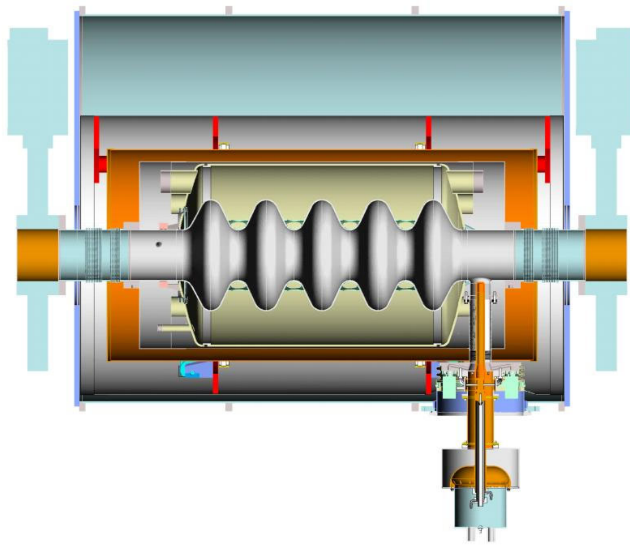

Figure 1: Computer graphic of 5 cell SRF cavity with cryomodule.

INTRODUCTION

Electron cooling will play a key role in the next RHIC luminosity upgrade. Electrons with a relatively low emittance are introduced into the ion beam at the same velocity. Energy exchange between ions and electrons results in a decrease in the longitudinal and transverse emittance of the ion beam. Cooling gold beams at 100 GeV/nucleon requires an electron beam energy of 54 MeV and a high average current of about 100 mA. Future projects such as eRHIC (electron-ion collider) may require an operational current of 300 mA-600 mA at 10 nC to 20 nC bunch charge. Such high currents and high energy electron beam call for an energy recovery superconducting linac to minimize power consumption. Four independent five cell superconducting cavities are proposed for the linac structure to accelerate the electron beam from the gun at 2.5 MeV to 54 MeV.

Higher order modes are one of the dominating factors influencing the design of high current cavities. These modes can give rise to two main problems that limit the performance and operation of a cavity:

1. Multi-pass, multibunch instabilities driven by high impedance dipole modes resulting in beam-breakup.

2. Power loss into the HOMs which must be removed safely from the cavity and cryogenic system. This paper describes an ongoing study of HOMs for developing an optimized design of a cavity, aimed at energy-recovery linac operation at an unprecedented current. Other aspects of the research program are design and construction of a complete cryomodule that is under development [8]. The R&D program includes the development of a complete energy recovery linac that will use the cryomodule as its linear accelerator to test the performance of the cavity under a fraction of an ampere CW current. A first prototype design has been approved for manufacturing. The production of the cryomodule is done as a joint effort of BNL's Collider-Accelerator Department and Advanced Energy Systems.

FIVE CELL SRF CAVITY DESIGN

Several factors influenced the choice of key parameters of the cavity.

1. A frequency choice of 703.75 MHz was made due to both physics and engineering issues. This is the 25th harmonic of the RHIC bunch repetition frequency with 360 buckets. A small loss factor from HOMs and the possibility of a larger aperture were important criteria. Also, engineering issues such as availability of high power CW klystrons and chemical cleaning facilities played an important role. A potential future use of this cavity in a linac-ring version of eRHIC (electron-ion collider) was also considered.

* Work performed under the auspices of the U.S. Department of Energy.

2. A five cell structure with a large aperture of 19 cm was chosen in the original design [1]. This choice was made in order to optimize the cavity for the best possible damping of higher order modes. However, after further investigation, the aperture of 17 cm was found to provide higher acceleration efficiency while effectively damping all HOMs.

3. Ferrite absorbers have proven successful in single cell cavities (CESR & KEK-B). Following the Cornell design, we adopted the use of ferrites in a 5-cell linac cavity. We will demonstrate that such HOM absorbers are adequate to damp all modes in our multi-cell cavity that might lead to beam instabilities. We plan to use two ferrite absorbers located along the beam pipe at room temperature. We also plan to install HOM couplers which may prove useful if we find unexpected trapped modes that weakly couple to the beam pipe.

Geometry

The cavity geometry was constructed by the “Build Cavity code”[3], a graphics interface software to Superfish. It allows the user to specify multi-cell cavity parameters and optimizes the cavity geometry through a series of Superfish runs. The new design of the 17 cm aperture with 24cm beam pipe diameter is shown in Fig. 2.

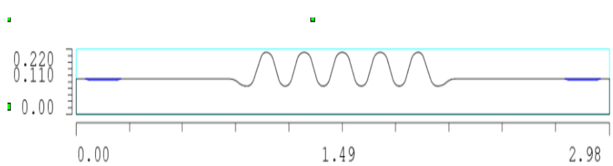

Figure 2: Build Cavity output in Mafia of 17cm geometry.

Ferrite absorbers are 24 cm in diameter and 20 cm in length as shown in Fig. 2 located outside the cryostat at room temperature. The ferrite material used is Ferrite-50 and is being manufactured by ACCEL according to the Cornell design **??**. Various parameters of the five-cell cavity are shown in Table 1. The optimum iris diameter of 17 cm is compared to an earlier choice of 19 cm.

Table 1: Cavity Characteristics

Diameter (cm)	17	19
Freq (MHz)	703.75	703.75
G (Ω)	225	200
R/Q (Ω)	807	710
Q @ 2k	4.5×10^{10}	4×10^{10}
E_p/E_a	1.97	2.10
H_p/E_a (mT/MV/m)	5.78	5.94
cell to cell coupling	3%	4.8%

For the calculation of Q at 2K, we assume $R_{BCS} = 3\, n\Omega$ and $R_{residual} = 2\, n\Omega$.

Field flatness and surface fields for the fundamental modes, calculated using 2D FEM code[4], are shown in Fig. 3, 4 & 5. vspace-0.4cm

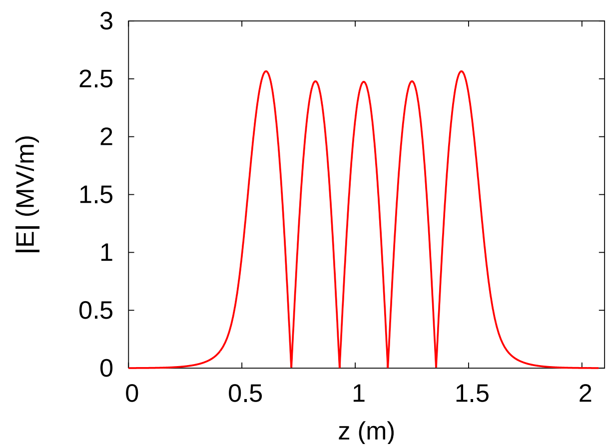

Figure 3: Field flatness of the fundamental mode peak-peak 96.5%.

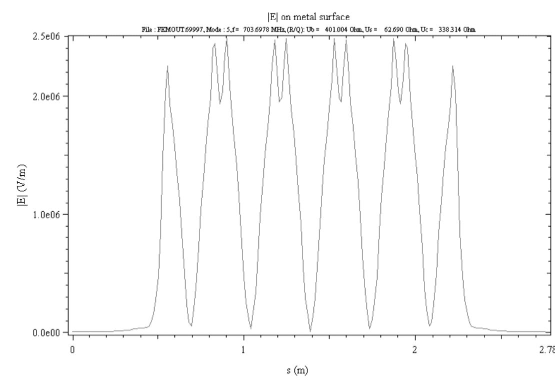

Figure 4: Surface electric field of the fundamental mode.

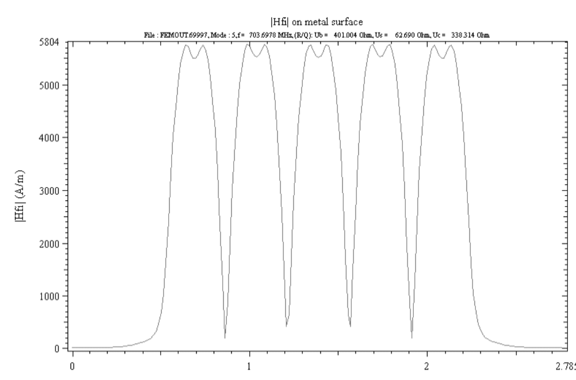

Figure 5: Surface magnetic field of the fundamental mode.

Higher Order Modes

Rigorous analysis of modes in a cavity is necessary to develop an efficient design. The complex structure of multi-cell cavities often cause modes to be trapped inside the cavity, thus limiting the performance due to beam instabilities. There are two main reasons for HOMs to become trapped inside the cavity structure:

1. The end cell geometry is different from that of the middle cells. This may result in poor cell to cell coupling and cause HOMs to get trapped inside the cavity structure.

2. It is also possible to find HOMs below the cutoff frequency of the beam pipe, preventing the mode from propagating out of the structure. These modes exponentially decay in the beam pipe before they reach the ferrite absorbers.

It is very important to carefully analyze such trapped modes and to modify the cavity structure to propagate them. It is common practice to use HOM couplers to couple out some harmful modes that exist in these complex structures. A preliminary design for couplers is underway. However, we propose a cavity design that will demonstrate the possibility of a high current operation with just ferrite absorbers placed in the warm section, thus minimizing cryogenic losses and simplifying critical engineering issues.

ANALYSIS OF TRAPPED MODES

The cavity is constructed in MAFIA [2] using "Build Cavity" output with beam pipe modifications including two ferrites placed on each side. The cavity is about 1 m long with beam pipes extending 1 m on each side of the end cells. We use the conventional E-module solver in MAFIA to calculate eigenmodes of the cavity. A thorough analysis of the original design using 19 cm aperture was presented in an earlier paper [1]. From previous analysis, the 19 cm design had 5 TE11n and 3 TM11n modes below cutoff frequency limiting the operation of the cavity at very high currents. It was initially proposed to increase the beam pipe diameter to 24 cm to propagate and damp these pseudo trapped modes. However, calculations using two different configurations proved that such an increase of beam pipe diameter is still inadequate to propagate some of the harmful TM11n modes.

A new design with a smaller cavity iris was proposed to improve acceleration efficiency and improve cell to cell coupling enabling the effective damping of HOMs with a reasonable aperture. The improvement in acceleration performance is clearly demonstrated in Table 1 between the 19 cm and 17 cm irises. For calculating HOMs we employ two methods, loss free and lossy analysis using MAFIA e-module.

Loss Free Case

In this method, two different boundary conditions (electric/magnetic) at the cavity ends are used to solve the eigenvalue problem in MAFIA. The corresponding frequencies are calculated and the influence due to change in boundary conditions is used to infer the presence of possible trapped modes. The factor k given in Eq. 1 is a measure of relative field strength between the middle cells and end cell.

$$k = \frac{1}{2}\left(\frac{f_{mag} - f_{ele}}{f_{mag} + f_{ele}}\right) \quad (1)$$

$$log\left(\frac{1}{k}\right) \approx \begin{cases} 0 & : \ untrapped \\ \infty & : \ trapped \end{cases} \quad (2)$$

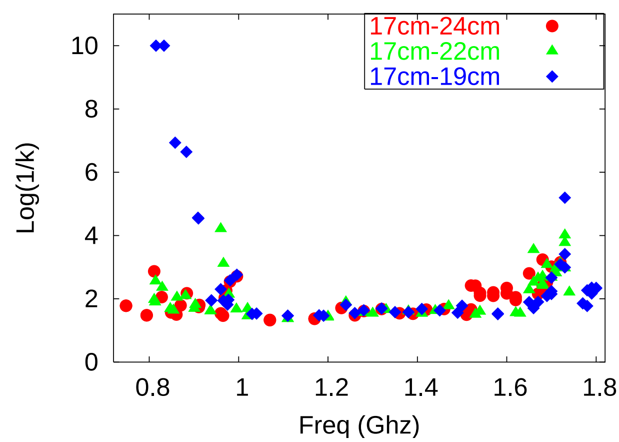

Figure 6: Analysis of trapped dipole modes in loss free case in 17 cm geometry.

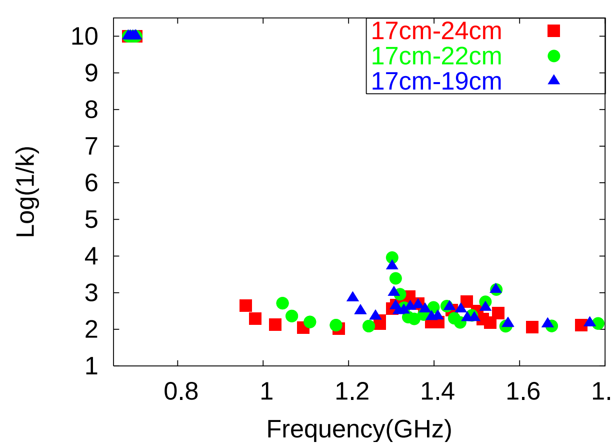

Figure 7: Analysis of trapped monopole modes in loss free case. Note fundamental modes at 0.7 GHz with high values.

This calculation was performed for 3 different configurations and the results are shown in Fig. 6. It is clear from the plot that the configurations using 17 cm iris with

24 cm beam pipe diameter is ideal to propagate all modes, especially the low frequency ones which contribute to instabilities. A similar calculation using boundary conditions were also performed for monopole modes and Fig. 7 shows $Log(1/k)$ as a function of frequency.

The R/Q values for the cavity modes can be easily computed using P-module in MAFIA. It is most desirable to design a cavity with high fundamental R/Q while keeping the R/Q for dipole modes as low as possible. We find that R/Q values for dipole modes are quiet small for our geometry. A few modes with the highest R/Q are shown in Table 3.

Lossy Case

In the lossy case, the calculations become significantly complicated and long. E-module offers two different possibilities for solvers, a complex invariant of the generic solver and the inverse solver. We use the inverse solver as recommended by the users manual and also due to the fact that the generic solver failed to give coherent results with complex shapes such as ours. We performed a calculation of dipole Q's with both generic (SAP) and inverse solvers without beam pipe modifications and found that they agree pretty well, as shown in Fig 8. The discrepancy around 2 GHz is due to simulation accuracy. To calculate accurate results around 2 GHz, one has to calculate modes to much higher frequency.

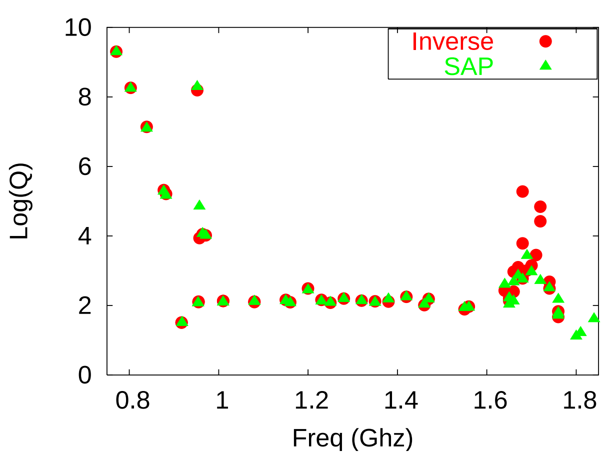

Figure 8: Dipole Q comparison of Inverse & SAP solvers in MAFIA using 19 cm geometry.

Quality Factor (Q) of Dipole Modes: Using the inverse solver we can determine the real and imaginary frequencies of the cavity modes and calculate their $Q's$, given by

$$Q = \frac{F_{real}}{2F_{img.}} \tag{3}$$

The Q values of the dipole modes can give a direct indication of possible trapped modes. Since small geometry changes do not change R/Q significantly, one can take advantage of this fact to cleverly shape the cavity to damp Q significantly without changing R/Q by a large amount. This allows one to have a better control over multibunch instabilities at high current operations. We investigate such a possibility of modifying our cavity design to damp Q's of dipole modes.

Detailed calculations using the original 19 cm geometry were performed and a 4 TE_{11x} like modes (740-760 MHz) and 3 TM_{11x} like modes (950-970 MHz) were found to have frequencies below the cutoff frequency of the beam pipe.

The cutoff frequency for a cylindrical waveguide is given by

$$f_c = \frac{c}{\pi D} X \tag{4}$$

where c is the speed of light and X is the root of the Bessel function or its derivatives as appropriate. Table 2 shows cutoff frequencies for a few diameters of interest.

Table 2: Cutoff Frequencies for Different Types of Modes

D(cm)	TM_{01}(MHz)	TE_{11}(MHz)	TM_{11}(MHz)
17	1350.94	1034.11	2152.5
19	1208.74	925.28	1925.9
24	956.92	732.51	1524.7

It is clear from Table 2 that an increase in aperture to 24 cm is required to propagate the TE modes, but a further enlargement to propagate the TM modes is not feasible. HOM couplers would be required to extract these modes. MAFIA calculations using different apertures were performed and Fig. 9 demonstrates the Q behavior as a function of aperture.

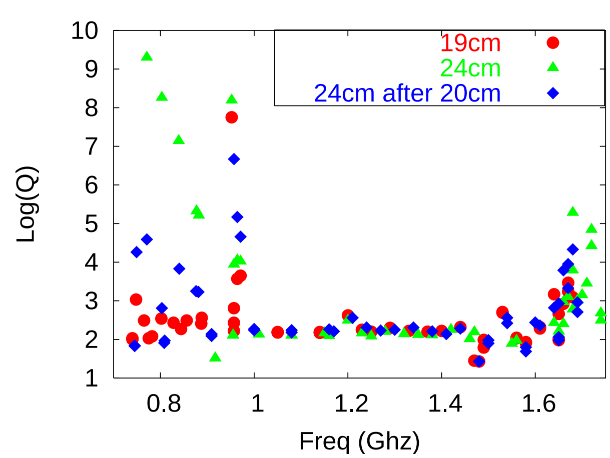

Figure 9: Dipole Q dependence for 19 cm geometry

The results from the 19 cm geometry prompted us to investigate a new cavity design with a smaller iris. The motivation was to increase the fundamental mode efficiency at the cost of trapping a few more HOMs that can be extracted using the HOM couplers. However, calculations with the new 17 cm geometry revealed quite spectacular results. The shunt impedance was increased by 10% and a beam pipe modification to 24 cm revealed a virtually HOM free cavity. Fig. 10 shows Q of dipole modes as a function of aperture and unlike the 19 cm geometry all modes are sufficiently damped. Q and R/Q values of particular modes interest are also shown in Table 3.

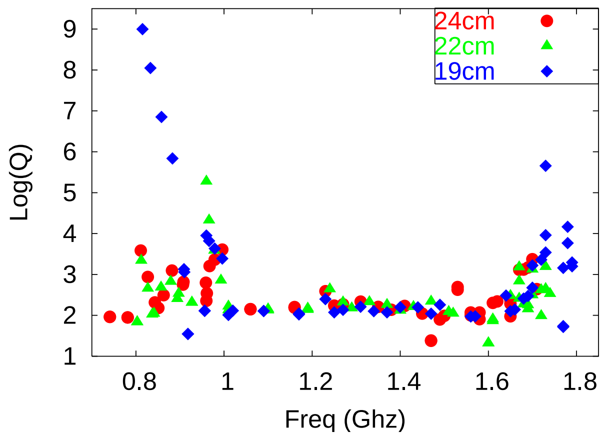

Figure 10: Dipole Q dependence for 17 cm geometry

Table 3: R/Q and Q Values for Few Dipole Modes of Interest

Frequency (MHz)	R/Q (Ω)	Q
862.6	30.1592	623.266
882.2	54.6518	2499.858
906.9	41.719	1133.058
967.1	3.5272	3212.957
979.2	3.7425	4608.0
995.7	1.7205	8088.546

The loss free analysis using different boundary conditions reveal the same phenomena as shown in Fig 6. Unlike the 19 cm geometry, we did not find any TM like modes below the cutoff frequency in 17 cm geometry. Thus, an increase in beam pipe to 24 cm was sufficient to propagate all dipole modes out of the cavity structure to be absorbed by the ferrites. This is evident from the Q values of the dipole modes. Since minor geometrical changes do not affect R/Q significantly, one can expect a big rise in beam break current in the new design.

This improvement can probably be attributed to two factors.

1. In a complex cavity structure, the EM modes are not purely TM or TE but probably a superposition. In the 19 cm geometry, 3 modes have a dominant TM part which prevents them from propagating through the beam pipe. However, similar modes in the 17cm geometry might have a dominant TE part, allowing them to propagate through the 24 cm aperture.
2. It is also possible for a cavity with poor coupling between middle and end cells to cause a mode to be trapped. A smaller iris improves coupling and might detrap some harmful modes. However, we did not find any significant evidence to attribute the trapped modes to coupling.

Comparison to Other Codes: A calculation using HFSS [5] was performed to crosscheck MAFIA results. Since HFSS only computes in 3D, the exact input used in MAFIA was replicated in 3D in HFSS and dipole $Q's$ were computed. We were able to extract the dipole $Q's$ of particular modes of interest. Fig. 11 shows that the values agree pretty well between MAFIA and HFSS. This is additional proof that our cavity structure is indeed HOM free.

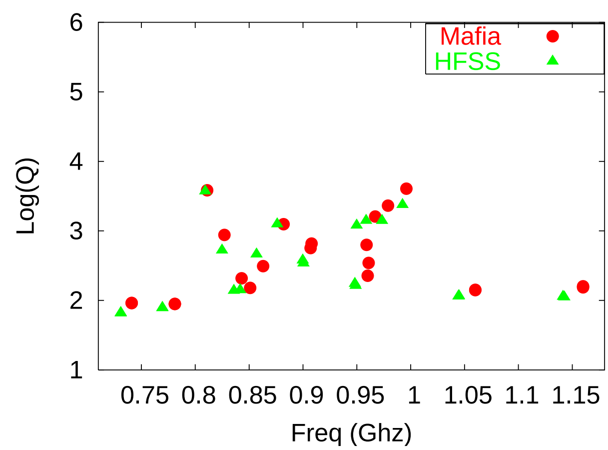

Figure 11: Dipole Q from MAFIA and HFSS for the 17 cm geometry

Mesh Dependence: For all the cavity calculations above we use 10^5 mesh points with the automesh feature. In a simple comparison analysis, we vary the number of mesh points and measure the dependence of Q values of dipole modes as a function of mesh points. Since the cavity structure under consideration for e-cooling has a 17 cm iris with a 24 cm beam pipe, we use this geometry for calculating $Q's$ with the aid of inverse solver. Fig. 12 shows that Q values start to converge at 10^4 mesh points. We use 10^5 mesh points to be on the safe side.

ϵ and μ Dependence: For all lossy calculations, epsilon and mu used were small. Table 4 shows properties of ferrite proposed for the cavity at frequencies of 1 GHz and the values used in MAFIA calculations.

Large imaginary values such as ferrite-50 yield inaccurate results because the solvers are unable to converge. However, we performed a calculation of Q values for dipole modes of interest with small increase in imaginary parts of ϵ and μ to understand the dependence. Fig. 13

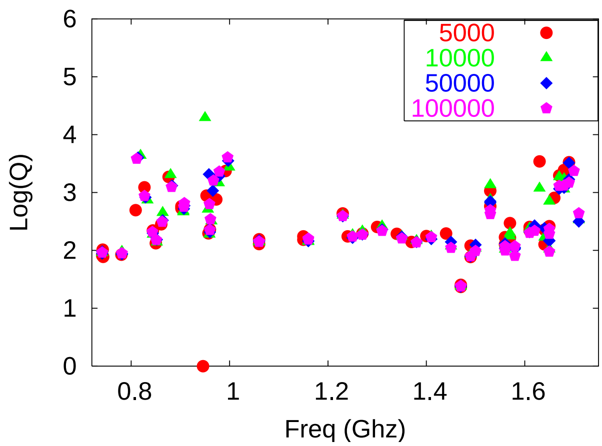

Figure 12: Dipole Q's as a function of number of mesh points for 17 cm geometry

Table 4: Cavity Characteristics

	Ferrite-50	Values Used in MAFIA
epsilon	(30.0, -10)	(10.0, -0.33)
Mu	(2.0, -100)	(2.0, -0.5)

demonstrates that dipole Q's decrease with an increase in imaginary ϵ and μ values, indicating that the real cavity with high loss ferrites should perform better than in simulation.

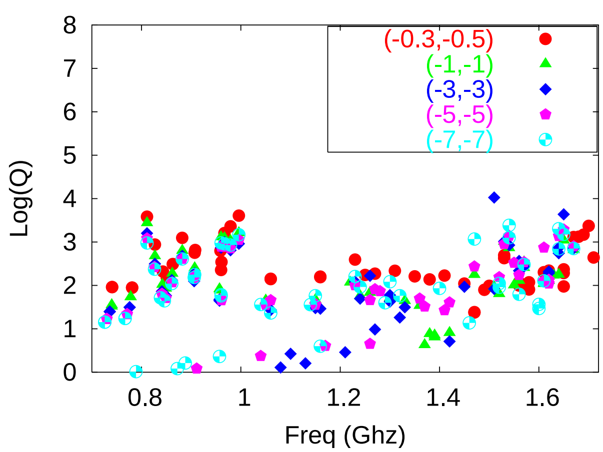

Figure 13: Dipole Q dependence on imaginary values of ϵ and μ in 17 cm geometry

Ferrite Location: The ferrites are not perfectly matched to the characteristic impedance of the beam pipe, resulting in some reflections and field variations as a function of position. From the proposed design, if one relies completely on ferrites to absorb the HOM power, it is important to match ferrite location to that of the maximum of the field strength. However, given the finite length (20 cm) of the ferrite, one cannot find an ideal location where every mode is to be matched perfectly. Since some modes have higher Q than others, one should choose a location with lowest Q configuration for all modes. This is under investigation, and the final location will probably be determined from test cavity results.

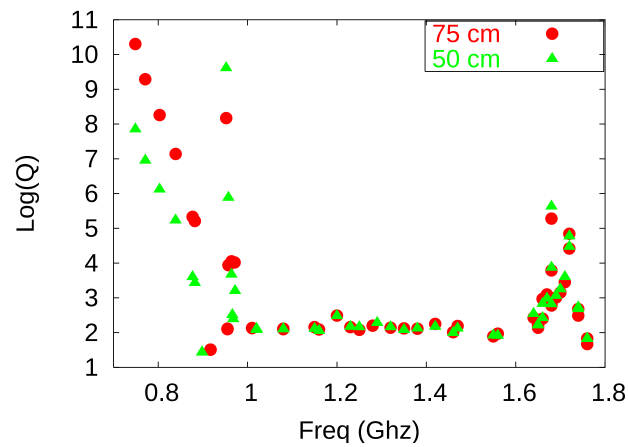

Figure 14: Dipole Q dependence on ferrite location for 19 cm iris with 19 cm beam pipe

A another factor to consider is the proximity of the ferrite to the cavity. It is desirable to place the ferrite close to the end cell in order to absorb the maximum power from exponentially decaying trapped modes that do not manifest themselves clearly in simulations. Fig. 14 demonstrates how location of the ferrite location affects Q values of trapped modes. This calculation was performed using the previous design with a 19 cm cavity iris with two different ferrite locations without any beam pipe modifications. It is clear from the plot that Q values are significantly lower when the ferrite is placed closer to the end cells. However, the same cavity iris with a 24 cm beam pipe shows no effect on the location because most of the modes are able to propagate to the ferrite and get absorbed. Ultimately, cryogenic issues determine how close the ferrite can be placed and possibly forcing one to use HOM couplers to extract any trapped modes.

MULTIBUNCH INSTABILITIES

The energy recovery mode, and high currents contribute strongly to coupled bunch instabilities due to poorly damped higher modes that limit the cavity performance. The low frequency dipole modes are particularly dangerous and can lead to beam breakup. Our new design of 17 cm iris and 24 cm beam pipe geometry looks very promising. We find most of the dipole $Q's$ to be small with a few of the order of 10^3, but still do not pose any significant threat. This remains to be checked in the high frequency range (above 2 GHz), but contributions from high frequency modes to beam break up are usually small. Also, we find that R/Q values are small for all modes which indicate high threshold currents for beam breakup. We use

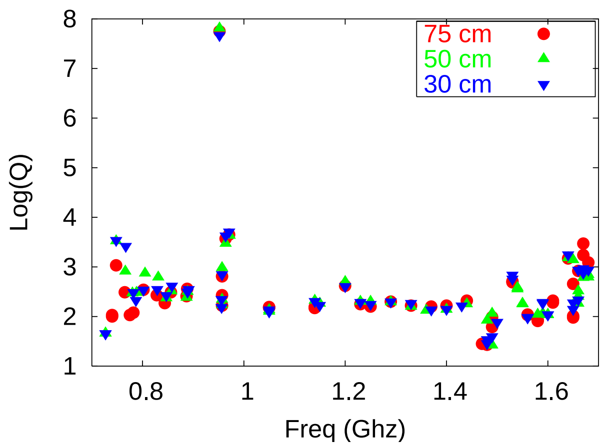

Figure 15: Dipole Q dependence on ferrite location for 19cm iris with 24 cm beam pipe

the TDBBU simulation code developed in Jefferson Laboratory [6] to calculate beam breakup thresholds from R/Q, Q, and corresponding frequencies, along with other beam parameters as input. We simulate each cavity as two drifts with an energy gain of 13.5 MeV with the HOMs placed in between the drifts. Using each dipole mode in both polarizations with a 15 MHz gaussian distribution, we obtain a threshold current of 1.8 A. Work is underway to accurately build cavity matrix and optics for the beam to propagate around the ring. In principle this should increase the threshold currents. A sister simulation software called MATBBU [7] was recently acquired from Jefferson Lab, which solves an eigenvalue problem to determine the threshold limits. Results from MATBBU show a threshold current of 1.85 A. Fig. 16 shows transverse beam position as a function of time calcualted by TDBBU for a current of 1.8 A. The intial (artificial) transverse kick decays, showing that 1.8 A is stable operation current.

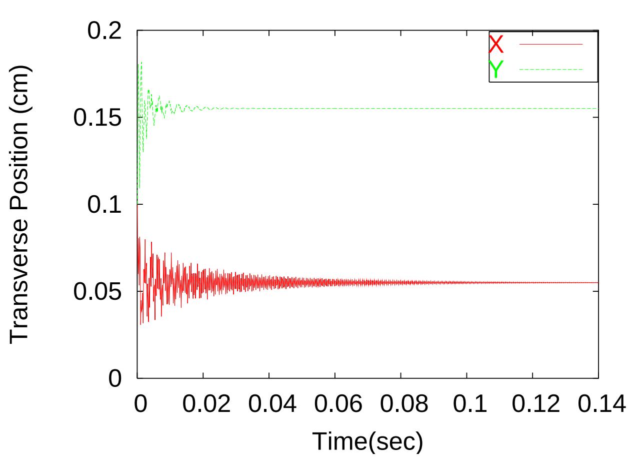

Figure 16: Beam breakup simulation using TDBBU with a threshold current of 1.8 A.

LONGITUDINAL LOSS FACTOR WALL LOSS & CRYOGENIC ISSUES

One of the major issues in SRF cavity design is power dissipated in the HOMs. High current and high bunch charge implies a huge HOM power that has to absorbed by Ferrite absorbers or extracted through HOM couplers. When this power becomes large it becomes a major cryogenic challenge, so it is imperative to keep HOM power loss to a minimum. The total HOM power is given by:

$$P_{HOM} = f_{beam} k_{loss} q^2 \quad (5)$$
$$P_{total} = \sum_n P_n \quad (6)$$

where f_{beam} is the beam repetition frequency at a bunch charge q, and k_{loss} is the loss factor which is given by

$$k_{loss} = \frac{1}{2\pi} \int_0^\infty Z_r(\omega) d\omega \quad (7)$$

In the neighborhood of the resonance frequency, the integral simplifies to the following expression.

$$k_{loss} \approx \frac{\omega_n R_n}{4Q_n} \quad (8)$$

where loss factor was calculated using ABCI, using a single bunch with a RMS length of 1 cm. Loss factor results are displayed below in Fig. 17 and 18.

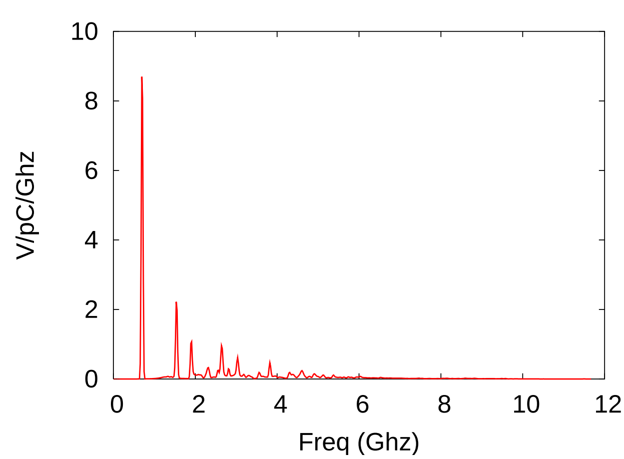

Figure 17: Loss factor as a function of frequency

Another important factor to consider is wall losses due to the fundamental mode in the beam pipe. Since part of the beam pipe is at 2K, it becomes crucial to minimize this loss for CW operation to be feasible. Preliminary calculations from the cryogenic group [10] indicate a maximum loss of 25 watts to be tolerable for a sustained CW operation. One can calculate this power loss from MAFIA. Results for a beam pipe length of 20 cm made of copper after the end cell with our present configuration show a total wall loss of 12

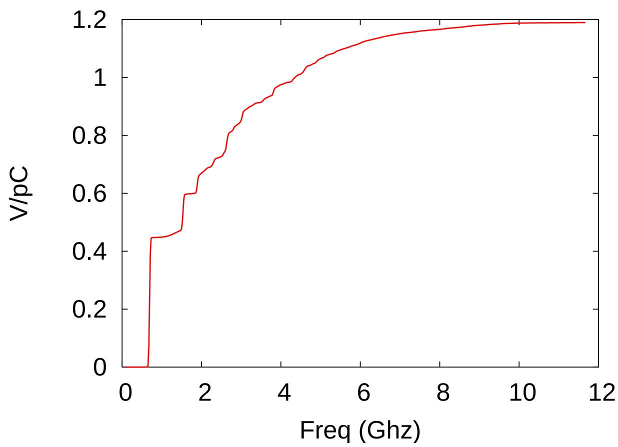

Figure 18: Integrated loss factor for 17-24cm geometry

watts on both sides of the cavity. We expect to intercept this power at liquid nitrogen temperature. The copper tube, also serving as a sheilding for the stainless steel bellows, will be anchored to the radiation shield and thermally isolated from the niobuim pipe. The electrical path for HOM power and beam image currents will be provided by a small capacitive element.

SUMMARY

A superconducting linac consisting of four 5-cell cavities is under development for very-high current energy-recovery linac operation. The cavity is designed to operate at 703.75 MHz. The design is characterized by large iris diameters of 17 cm to reduce the loss factor (and thus total HOM power loss) and with a beam pipe diameter of 24 cm, for efficient propagation of HOM power to the ferrite absorbers. The cavity shape was developed using the Build Cavity code. The cavity dipole modes were calculated by MAFIA simulations (and checked against HFSS). The R/Q and Q values for a large number of HOMs were introduced into the code TDBBU in a small 54 MeV energy recovery linac. The ERL threshold current for the multi-bunch multi-pass beam breakup was calculated by TDBBU at over 1.8 A.

ACKNOWLEDGEMENTS

We thank the entire e-cooling team at BNL for their valuable suggestions and concerns. We would like thank the CASA group from Jefferson Laboratory in particular L. Merminga, B. Yunn and K. Beard who provided us with beam breakup software and helped us in optimizing our cavity design. We would also like to thank the SRF group at Jefferson Lab in particular B. Rimmer and H. Wang for their suggestion on our cavity design.

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