Study of High T_c Superconducting MgB_2 Thin-Film Coated Radio Frequency Cavities

Ashley Ernst, Ohio Northern University, Ada, OH
Supervisors: Ali Nassiri and Bob Kustom, Argonne National Laboratory, Lemont, IL

Abstract

Studies show promise in magnesium diboride, a high critical temperature superconducting material, for its application in cryogen free radio frequency cavities. The performance of a cavity is limited by the impurities in the magnesium diboride coating from cavity preparation and production, therefore, a system to test the quality of the coating for samples must be developed. Microwave Studio, a simulation software was used to design an optimal open resonator model for testing the quality of such coupons. Based on a previously reported cavity, a Fabry-Perot open resonator was scaled to 30 GHz and optimized. The results of the simulations are presented.

INTRODUCTION

Superconducting radio frequency (RF) cavities are used in particle accelerators around the world. Typically the superconducting material used is niobium which requires the use of cryocoolers and cryogens to maintain the necessary temperature. Recent studies [1] have shown promise in magnesium diboride, a new superconducting material for superconducting RF cavities. The use of magnesium diboride would allow for the elimination of cryogens from the RF system which would greatly simplify the system. However, cavity performance is limited by impurities in the coating which result from cavity preparation and production. Thus, a technique must be developed to test the quality of thin film coated coupons created using various deposition techniques. A paper by Martens [2] demonstrated a Fabry-Perot resonator that could be scaled to operating frequencies that would be optimal for testing such coupons.

SUPERCONDUCTING MATERIAL: MAGNESIUM DIBORIDE

Magnesium diboride has shown promise in studies for application in superconducting RF cavities. The critical temperature of magnesium diboride is 39 K compared to niobium which is only 9 K [1,3]. While there are many superconducting materials with higher critical temperatures than niobium, magnesium diboride is the first to show promise for use in superconducting RF cavities. Most high critical temperature materials have the problem of a rapid increase in RF surface resistance with higher surface magnetic fields. Magnesium diboride has demonstrated little increase in the RF surface resistance and has even shown that the RF surface resistance can be lower than that of niobium at 4 K [3]. Through recent studies [4], it has been seen that the same surface resistance can be achieved at 8-12 K with magnesium diboride that is achieved with niobium at 4 K. Generally, cavities are restricted by the quench field of niobium of 50 MV/m and the use of magnesium diboride would allow for the increase in the accelerating gradient beyond that limit [1].

Studies of magnesium diboride show feasibility for designing helium-free superconducting RF cavity systems using cryocoolers operating in the 8-12 K range.

FABRY-PEROT OPEN RESONATOR

Fabry-Perot open resonators are used for many applications due to their strong field confinement and quasioptical nature [5]. A Fabry-Perot resonator is an optical cavity with parallel spherical or parabolic mirrors. In many cases, spherical mirrors are used to focus waves without energy lost due to diffraction. Classically, the spherical mirror structure is set up so that the center of curvature of each mirror is at the other spherical surface; therefore the radius of curvature is equal to the separation between the mirrors. This causes a more narrow beam waist at the sample in the center of the system. These resonators are used for millimeter-wave surface resistance measurements of high temperature superconducting films because of the simplicity of structure, relative insensitivity of the experimental design to frequency, and the very high quality factors that are obtainable [5]. The resonator allows for separate measurements of the heat deposited onto the sample and into the rest of the cavity structure.

For this experiment, the half confocal resonator was simulated. In this case, the sample is placed at the center of the system and the second mirror is removed. This is possible because the fields are nearly plane waves at the center of the structure and the magnetic field is at a maximum at the sample. The

$TEM_{0,0,q}$ modes of the cavity, found at $f_{0,0,q}$, induce magnetic fields onto the sample. The magnetic fields result in measurable heat loads on the sample which can be used to test the quality of the coating. The resonant frequency of each TEM mode can be obtained with the following equation [6].

$$f_{0,0,q} = \frac{c}{2D}[q + 1 + \frac{1}{\pi}cos^{-1}(1 - \frac{D}{R})]$$

The parameter D represents the length of the full resonator or twice the length of the half resonator system that was used in this experiment, R is the radius of curvature of the mirror, and q is the mode number corresponding to the full resonator.

SIMULATION

The resonator used in this experiment was initially a scaled version from a paper by Martens. Previously in this experiment, a resonator at 8 GHz was used due to an available traveling-wave tube amplifier at that frequency. The resonator demonstrated that 8 GHz was too low to contain the field within a 2 inch coupon. For the current project, the frequency of 30 GHz was chosen due to commercially available amplifiers at that frequency. Because of the frequency choice, the wave guide entering the resonator is a WR-28, the standard size for this frequency.

Using the time domain solver in CST Microwave Studio, the resonator was optimized to result in the highest heat load deposited onto the sample while maintaining the mode that was desired. Aspects of the resonator that were varied during optimization include the radius and height of curvature of the mirror, the coupler radius, the separation between the mirror and the sample, and the radius of the sample.

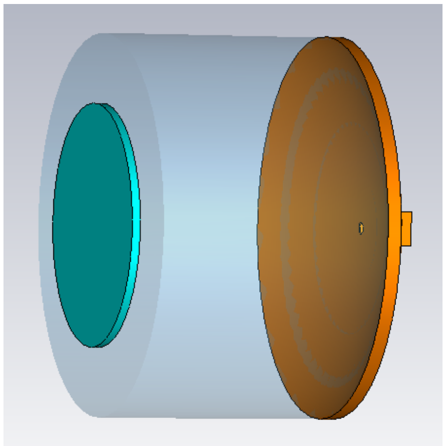

Figure 1: *Diagram of the open resonator with dimensions listed in table1.*

Another resonator that was attempted was a closed resonator of the same dimensions as the open resonator with a copper shell with a thickness of 0.3 millimeters. This was used to force a trapped mode in the resonator. For this resonator, all of the power should be loss into the walls of the cavity.

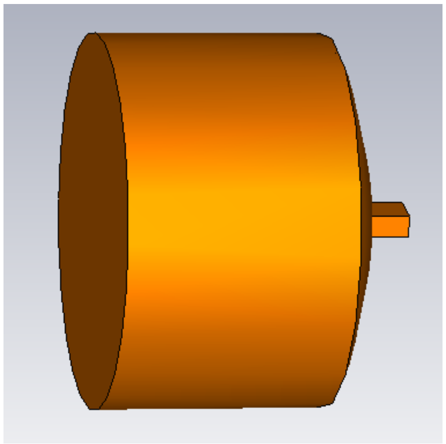

Figure 2: *Diagram of the closed resonator with dimensions listed in table 1.*

Description	Scaled Value	Ideal Value
Frequency	30.11 GHz	29.80/29.78 GHz
Radius of mirror	110 mm	110 mm
Height of curvature	45.72 mm	45.72 mm
Coupler Radius	1.50 mm	1.77 mm
Separation	66.00 mm	66.00 mm
Radius of sample	25.40 mm	29.05 mm

Table 1: *Dimensions of the open resonator that was scaled from a paper by Martens [2] (scale factor of 1.2) and of the resonator (open/closed) that results in the highest power dissipated onto the sample.*

SIMULATION RESULTS

While maintaining the desired mode, as seen below, many of the listed aspects did not change from the scaled numbers. This was expected due to the optimization of the resonator by Martens [2]. However when varying the dimensions of the resonator, only small differences were observed in the amount of power dissipated onto the sample. Changing the dimensions of the system should have resulted in larger differences in the amount of power dissipated onto the sample. This could be because of the amount of power dissipated out of the system. For example when changing the radius of the sample, the amount of power dissipated into the sample is expected to increase as the sample size increases. However, the power dissipated into the sample was fairly consistent among all the sample sizes.

Even after the optimization of the resonator the amount of power dissipated onto the sample was very small, only 0.35 percent of the total power put into the resonator while approximately 99.2 percent of the power is still in the system or has been lost according to the scattering parameters. This power dissipated onto the sample should have been much larger and shows that the mode was not trapped in the resonator. Energy was dissipating out of the sides of the resonator.

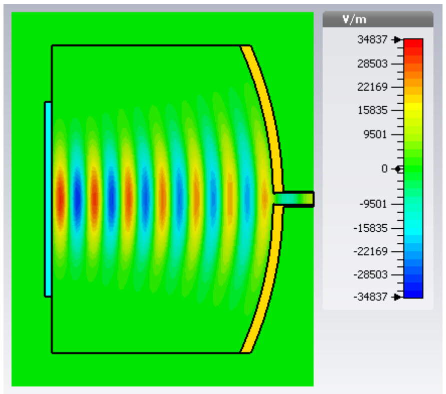

Figure 3: *Cross-sectional view of the electric field pattern for the open resonator in the desired mode,* $TEM_{0,0,26}$.

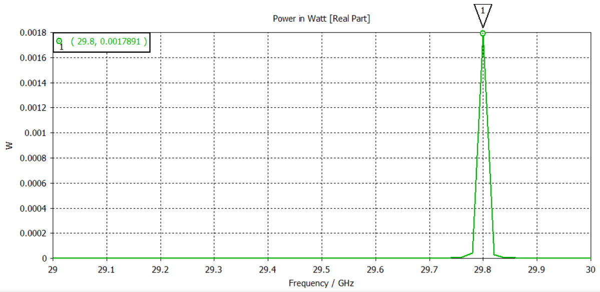

Figure 4: *Graph of the power loss into the sample for the open resonator where the total power entering the resonator is 0.5 watts. The marker represents the frequency of the desired mode.*

Due to the amount of energy that dissipated from the system, the closed resonator was considered to try to measure how much power was escaping confinement in the open resonator. However, a similar problem was seen with this resonator as the previous. The total amount of power dissipated into the resonator walls was only 4.97 percent of the total power that entered the resonator. According to the scattering parameters, approximately 46.2 percent of the total power that entered the system has not propagated. The amount of power dissipated into the walls should be orders of magnitude greater and should approach 100 percent as the simulation is run for longer periods of time resulting in a smaller amount of power that has not propagated. This demonstrates that the energy of the system is being reflected back from the cavity.

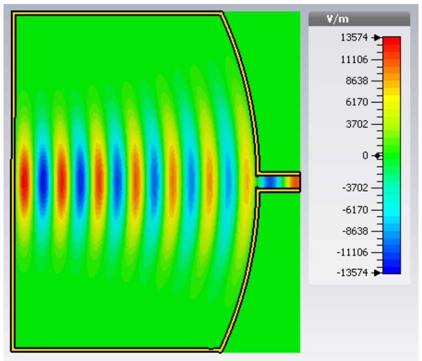

Figure 5: *Cross-sectional view of the electric field pattern for the closed resonator in the desired mode,* $TEM_{0,0,26}$.

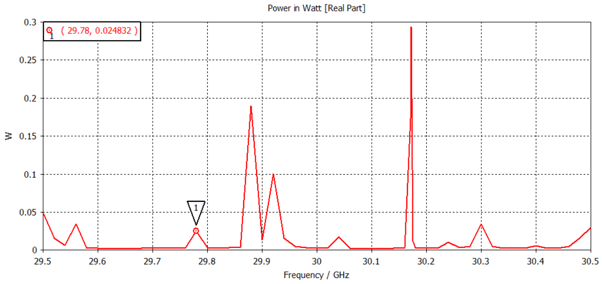

Figure 6: *Graph of the power loss into the sample for the closed resonator over a frequency range where the total power entering the resonator is 0.5 watts. The marker represents the frequency of the desired mode. The other frequencies are those of higher order modes.*

Additionally, as can be seen from the graphs of the power loss in the sample, adding the shell around the system caused the frequency to shift. The shell should not affect the frequency at which the open mode is present.

SUMMARY

Development of magnesium diboride thin-film coated radio frequency cavities would allow simplification of the RF systems in accelerators due to the ability to operate at higher temperatures. Operating at higher temperatures would eliminate the need for cryogens and the equipment used for the storage and transfer of cryogens.

The quality of the coating greatly affects the performance of the cavity. Therefore, a mechanism must be developed to effectively test the magnesium diboride thin-film coated copper coupons. Initial simulations using Fabry-Perot open resonators was examined but found that the power dissipated onto the sample does not produce a large enough heat load to measure. In order to determine the reason for this, the closed resonator needs to be looked at more closely with the walls and the sample split into different pieces. This should provide data on exactly where the power is dissipated onto the cavity and will hopefully provide some insight into the reason for the open and closed resonators not matching up.

Acknowledgements

I would like to thank my supervisor Ali Nassiri for the opportunity to work with the RF group in the Accelerator Systems Division. Additionally, I would like to thank Bob Kustom for his guidance throughout this experience and Geoff Waldschmidt for his patience and assistance with using Microwave Studio. Lastly, for providing the opportunity, I must thank the Lee Teng Undergraduate Fellowship in Accelerator Science and Engineering program and its coordinators, Eric Prebys and Linda Spenzouris.

References

[1] Xi, X X. 2009. MgB_2: Thin Films. Supercond Sci Technol 22 (043001):15pp.

[2] Martens, J.S., et al. 1991. Confocal Resonators for Measuring the Surface Resistance of High Temperature Superconducting Films. Appl Phys Lett 58 (22): 2543-2545.

[3] Tajima, T. 2005. Power Dependence of the RF Surface Resistance of MgB_2: Superconductor. Particle Accelerator Conference PAC05: 4215-4217.

[4] Oates, D.E., et al. 2010. Microwave Measurements of MgB_2: Implication for Applications and Order-Parameter Symmetry. Superconduct Sci Technol 23(3):034011.

[5] Clarke, R.N and Rosenberg, C.B. 1982. Fabry-Perot and Open Resonators at Microwave and Millimetre Wave Frequencies, 2-300GHz. J Physics E: Sci Instrum 15 (9): 9-24.

[6] Cullen, A. 1983. Millimeter-Wave Open Resonator Techniques. Infrared and Millimeter Waves V10: Millimeter Components and Techniques, Part 2: 244.

[7] Nassiri, A., et al. 2013. Cryogen-Free RF System Using Cryocoolers-Cooled Magnesium Diboride-Coated Copper RF Cavities. Conference on RF Superconductivity, SRF2013, 657-659.