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Project: Advanced Instrumentation for Cryogenic Testing of Superconducting Microwave Cavities

Introduction

The acceleration of particles is of great interest to physicists for a variety of uses, such as the production of X-ray radiation here at Cornell. One method of accelerating particles is through the use of superconducting radio-frequency (SRF) cavities, ovoidal-shaped enclosures that contain standing electromagnetic waves (Figure 1). At Cornell, the cavities are made of pure niobium, Nb_3Sn, or nitrogen-doped niobium, with the focus of the SRF research group being on the latter two.

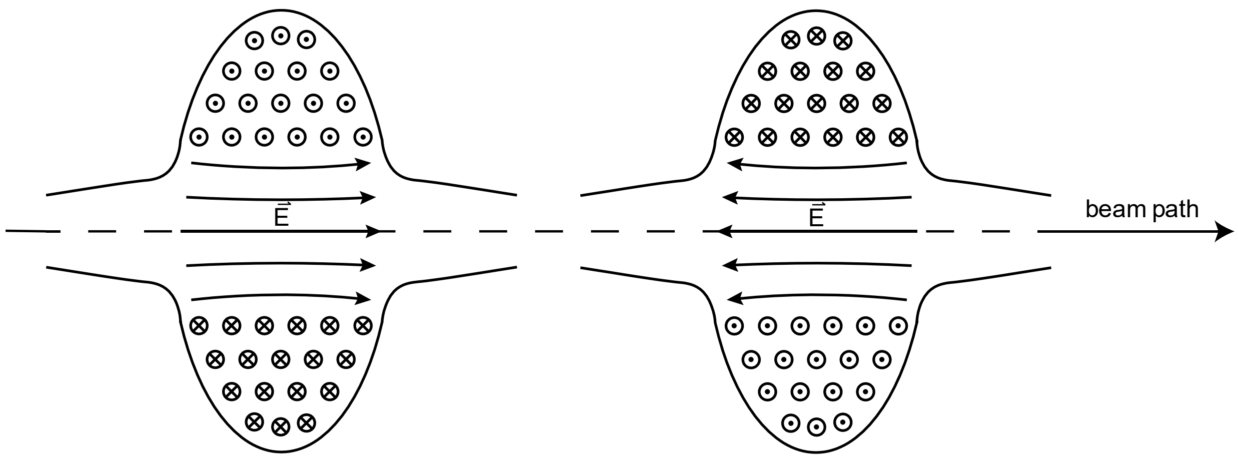

Figure 1: Two stacked SRF cavities resonating at the TM_{010} mode

Standing EM Waves

Radio-frequency (RF) cables are used to send electromagnetic radiation to an antenna contained within the cavity to make an oscillating standing electromagnetic field inside the cavity. For most SRF accelerator cavities, the radiation resonates in what's known as the TM_{010} mode, where the three subscripted numbers describe the geometry of the standing wave along the φ, r, and z components of a cylindrical coordinate system superimposed over an idealized "pillbox"-shaped SRF cavity. Particles incident on the electric field are caused to accelerate due to the field's gradient. If many cavities are stacked, the arrival of particles can be timed such that they experience a linear acceleration along the direction of the beam path.

Superconductivity

Superconductors are materials wherein the DC resistivity drops dramatically to zero below a certain temperature, called the critical temperature. According to the Bardeen–Cooper–Schrieffer (BCS) theory of superconductivity, this happens because electrons in the material bind into what are known as

Cooper Pairs, which can carry the current in the superconductor while encountering essentially no resistance. When alternating currents are used on a superconductor, the inertia of these Cooper Pairs does cause a little surface resistance, but it is certainly nothing close to what one would get using a normal conductor.

Quality Factor

A vital quantity of a given SRF cavity is its quality factor (Q-factor). The Q-factor of a cavity is given by

$$Q = \omega_0 U/P,$$

where ω_0 is the angular frequency of the system, U is the energy put in via EM radiation, and P is the power dissipated from the cavity due to the inertial resistance of oscillating cooper pairs. Due to their superconducting nature, the Q-factor for SRF cavities can be on the order of 10^{10} [1]. To measure the Q-factor, it is necessary to know the energy put into the cavities through the RF cables. However, the energy that reaches the cavities is lower than the energy output by our power supplies due to attenuation within the cables. This power loss cannot simply be factored in to Q-factor calculations, as it is highly dependent upon the geometry of the cables.

Cataloging & Replacing High-Attenuation RF Cables

To address the attenuation issue, a catalog was made of all RF cables in the basement at Newman Laboratory, and high-attenuation cables are being replaced with low-attenuation ones. A diagram was also made of all active cables being used for the cavity test pits (Figure 2).

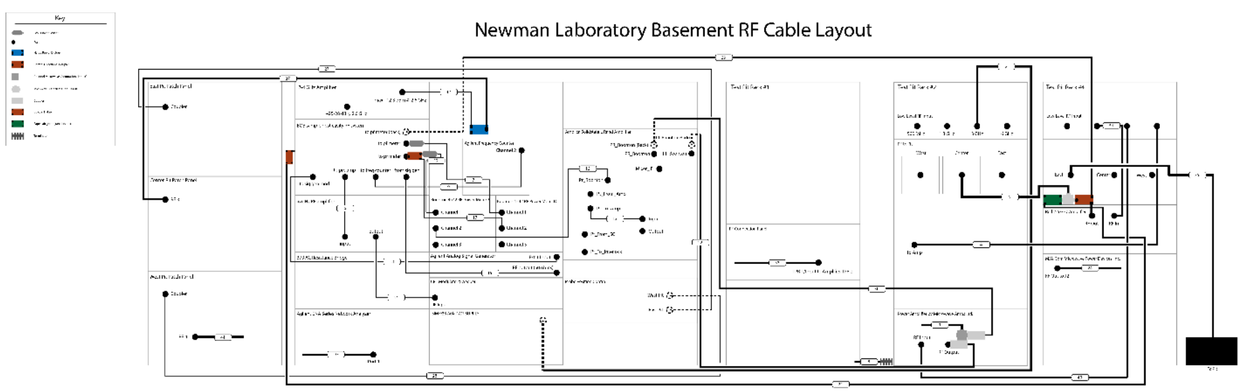

Figure 2: Schematic of the Newman basements

Anti-Q Slope

As mentioned earlier, chiefly two cavity materials are studied by Cornell's SRF group: Nb_3Sn and nitrogen-doped niobium. With normal SRF cavities, the Q-factor decreases as the electric field inside increases (Figure 3); this is to be expected and the cause is well understood. However, in the case of the nitrogen-doped niobium cavities, the opposite effect is observed: The Q-factor increases as the electric field increases (Figure 4) [2]. Another way of looking at this phenomenon, dubbed the “anti-Q slope”, is that the surface resistance of the cavities decreases as the magnetic field increases, where the surface resistance is equal to the sum of the temperature-dependent BCS resistance and the temperature-independent residual resistance. BCS resistance is the resistance accounted for by BCS theory, while the residual resistance is caused by impurities and other effects.

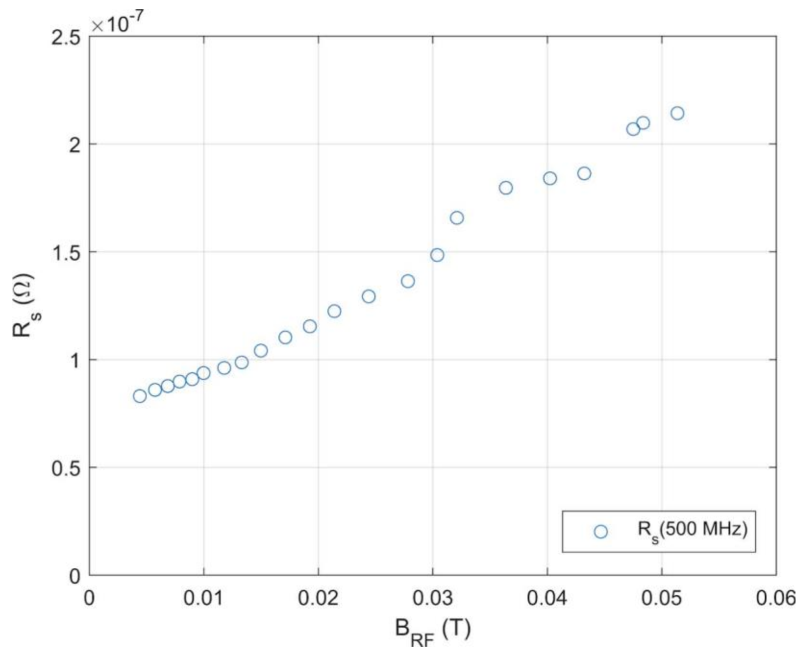

Figure 3: Surface resistance v. RF magnetic field of a non-nitrogen-doped SRF cavity [3]

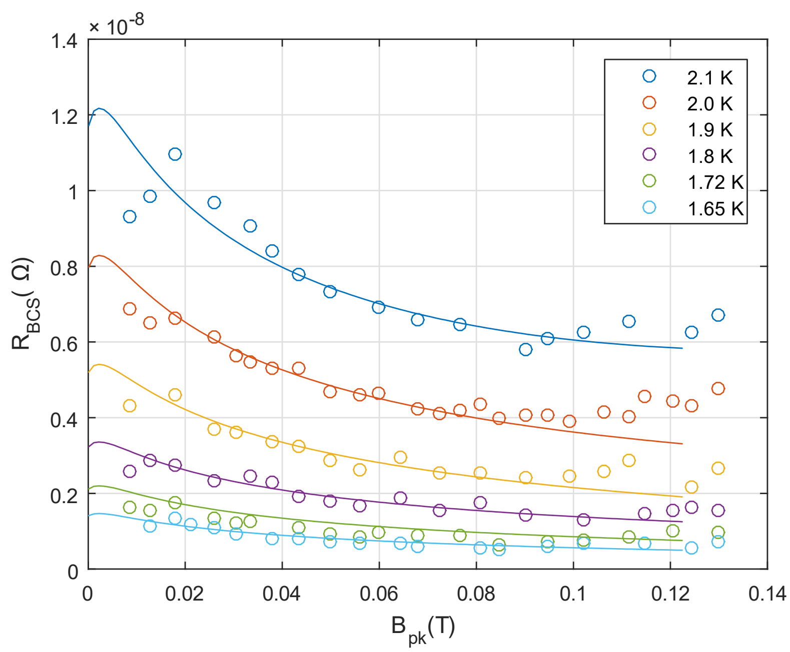

Figure 4: BCS resistance v. peak magnetic field representation of the anti-Q slope of nitrogen-doped niobium cavities [4]

The cause of this anti-Q slope is not yet known, though a few models have been proposed. One such model, proposed by Alexander Gurevich, is to be tested at Cornell [2]. James Maniscalco has designed a cavity that will enable us to test Gurevich's model by examining the change in surface resistance of a superconductor caused by a *steady* magnetic field from a high-current superconducting electromagnet (as opposed to the changing RF field) (Figure 5) [5].

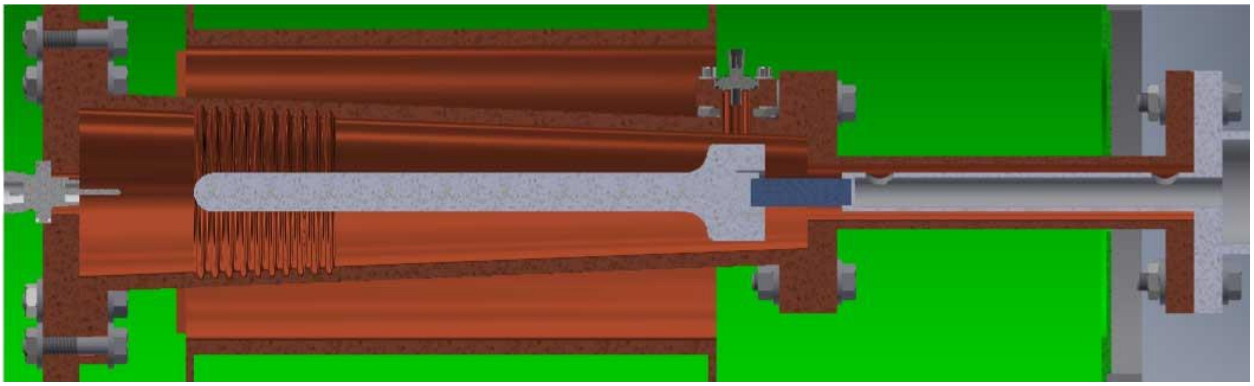

Figure 5: CAD drawing of James Maniscalco's anti-Q slope cavity design [5]

To eliminate excessive forces and electrical risks due to the high currents and fields involved, a program was developed in MATLAB to allow for steady changes to the current and voltage across our electromagnet to avoid damaging our coil. The program interfaces with a power supply, allowing the user to set a desired current to be reached over a specified period, allowing the power delivered to the cavity to slowly increased from zero.

Summary & Acknowledgments

Instrumentation for testing SRF cavities was improved by cataloging RF cables and preparing to order lower-attenuation ones to improve Q-factor measurements. A diagramming of all active cables in the basement of Newman Laboratory was also undertaken. Software was built in MATLAB to allow the safe delivery of power to a new cavity designed to test Alexander Gurevich's hypothesis on the cause of the anti-Q slope.

This work in the SRCCS program would not have been possible without the assistance of the National Science Foundation through the Cornell High Energy Synchrotron Source (CHESS), award number DMR-1332208. I would also like to thank James Maniscalco and Matthias Liepe for their assistance throughout these past two months, both with direction and consultation.

References

[1] J. T. Maniscalco et al., "The importance of the electron mean free path for superconducting radio-frequency cavities", Journal of Applied Physics, vol. 121, no. 4, p. 043 910, 2017.

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[3] F. Furuta et al., "RF Test Result of N-Doped 500 MHz B-Cell Cavity at Cornell With BNL", in Proceedings of IPAC2018, Vancouver, BC, Canada, 2018.

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