SUPERCONDUCTING CAVITY FOR THE MEASUREMENTS OF FREQUENCY, TEMPERATURE, RF FIELD DEPENDENCE OF THE SURFACE RESISTANCE*

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Abstract

In order to better understand the contributions of the various physical processes to the surface resistance of superconductors, the Old Dominion University (ODU) Center for Accelerator Science (CAS) is developing a half-wave resonator capable of operating between 325 MHz and 1.3 GHz. This will allow the measurement of the temperature and RF field dependence of the surface resistance on the same surface over the range of frequency of interest for particle accelerators and identify the various sources of power dissipation.

MOTIVATION AND RESEARCH OBJECTIVES

The surface resistance is the fundamental source of power dissipation. Yet, we do not have a complete understanding of the loss mechanisms. For a low field region the Bardeen-Cooper-Schrieffer (BCS) theory provides the determining factors such as critical temperature (T), frequency (ω), and material properties of penetration depth (λ), energy gap (Δ), coherence length which expressed as following [1]:

$$R_{BCS} \cong \frac{\mu_0^2\omega^2\lambda^3\sigma_n\Delta}{k_BT}\ln\left[\frac{C_1k_BT}{\hbar\omega}\right]\exp\left[-\frac{\Delta}{k_BT}\right].$$

Here μ_0, k_B, $\hbar$ are permeability in free space, the Boltzmann constant, and the Planck constant respectively.

The test results of actual cavities show that there is a temperature independent residual resistance (R_{res}), which remains unexplained. Several contributions (e.g.; trapped vortices, metallic suboxides or hydrides, grain boundaries, etc [1]) to the residual resistance have been studied. They all seem to contribute to the loss but largely on a case by case basis. So far the residual resistance tends to be treated as a material defect rather than a fundamental intrinsic phenomenon.

One of the basic limitations of all the experimental work to-date is that the tests have been performed on each cavity or surface at a single frequency. To vary the frequency, different cavities were built and tested. Even with careful control, fabrication techniques do not guarantee identical, repeatable surfaces. This variation adds difficulty when attempting to extract accurate frequency dependence. Even when the same cavity was measured at different frequencies in different modes, typically elliptical cavities where the frequencies were relatively close, the surface magnetic and electric field distributions were quite different in the various modes. To be able to systematically study the frequency dependence, the cavity should provide the identical surface and the same field distribution. This requires a multi-mode cavity. A simple geometry that would fulfill those requirements is a cylindrical coaxial resonator [2] shown in Fig. 1.

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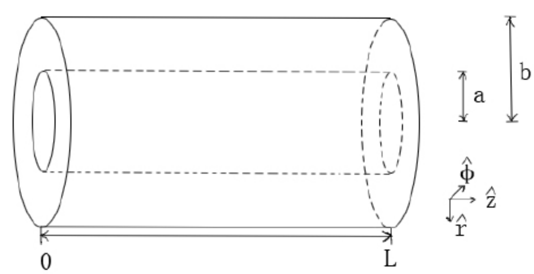

Figure 1: Coaxial half wave resonator.

ODU CAS optimized and fabricated such a cavity and are ready to carry out the experiments to see the frequency, field, temperature dependence of the surface resistance.

ELECTROMAGNETIC DESIGN

Cavity Parameters

Besides the usual TE and TM modes in cylindrical resonators, a coaxial resonator has a series of TEM modes where the high surface magnetic field is concentrated on the inner cylinder with the same sinusoidal profile (although of different wavelength).

Its simple geometry allows analytical solutions of Maxwell's equations [3] as follows.

$$\boldsymbol{E}_T = \hat{r}\frac{V_0}{\ln\left(\frac{b}{a}\right)}\frac{1}{r}\sin\left(\frac{n\pi z}{L}\right)e^{-i\left(\omega t-\frac{\pi}{2}\right)}$$

$$\boldsymbol{H}_T = \hat{\varphi}\,\frac{V_0}{\ln\left(\frac{b}{a}\right)}\frac{1}{r}\sqrt{\frac{\varepsilon_0}{\mu_0}}\cos\left(\frac{n\pi z}{L}\right)e^{-i\omega t}$$

where V_0 is the peak voltage at the inner conductor and ω is the RF frequency.

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The length is optimized to have the frequencies of interest in accelerators around the world.

The peak magnetic field occurs on the inner conductor surface. Therefore, the smaller inner conductor radius reduces the heating. At the same time it has to be reasonably easy to fabricate the tube and to provide sufficient liquid helium flow. A radius of 20 mm was chosen. Then the outer radius was optimized to separate the TE modes far from the TEM modes. Table 1 illustrates the resulting cavity parameters after the four ports were added. The modes and their frequencies are shown in the Table 2.

Table 1: Cavity Parameters

Parameters	Unit	Value
Cavity length	Mm	459
Outer conductor radius	Mm	20
Inner conductor radius	Mm	101
Peak electric field, E_p^*	MV/m	16
Peak magnetic field, B_p^*	mT	53
Geometric factor, G	Ohm	59, 119, 179, 239[#]

* For 1 J energy content.
\# For the TEM modes respectively.

Table 2: Mode and Frequency

Mode	Frequency [MHz]
TEM1	325.4
TEM2	650.8
TE111	869.6
TEM3	976.1
TE112	1035.9
TE113	1265.4
TEM4	1301.3
TE211	1470.1

The field distributions are shown in Figure 2 for the electric field and in Figure 3 for the magnetic field. Both fields are concentrated on the inner conductor surface and show sinusoidal distribution as the equations indicated.

The following figures are showing only for TEM modes of interest.

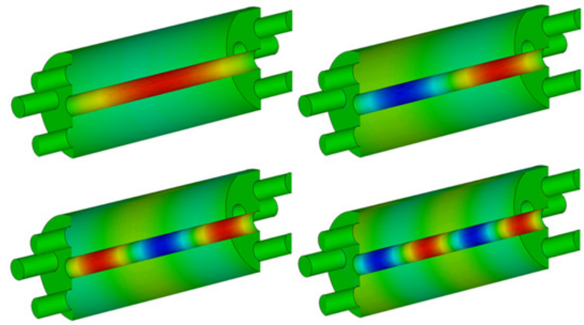

Figure 2: Cavity showing surface electric field distribution from top left clockwise TEM1, TEM2, TEM3, and TEM4.

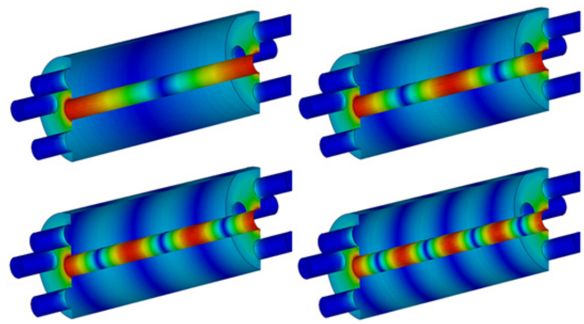

Figure 3: Cavity showing surface magnetic field distribution from top left clockwise TEM1, TEM2, TEM3, and TEM4.

Multipacting Study

Multipacting analyses were performed using Track3P of SLAC ACE3P [4] to determine if any modification of the cavity geometry is necessary and also to investigate where one will encounter multipacting during testing. The lower frequency modes have a negligible number of resonant particles up to 150 mT. The TEM4 mode shows a possibility that multipacting might occur in the range between 70 to 100 mT. Figure 4 shows the location of the resonant particles where largely occurring on the end cap surface. The impact energy over the magnetic field amplitude is plotted in the Figure 5.

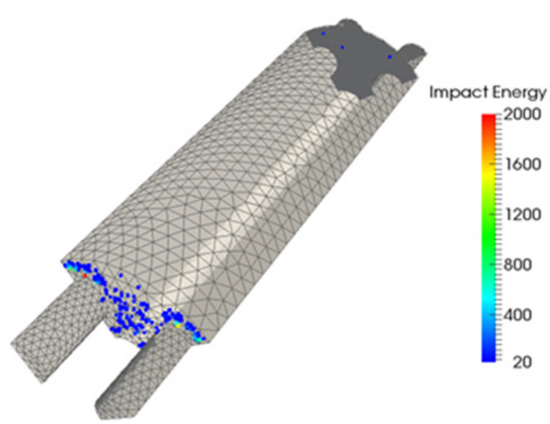

Figure 4: Resonant particles on cavity surface.

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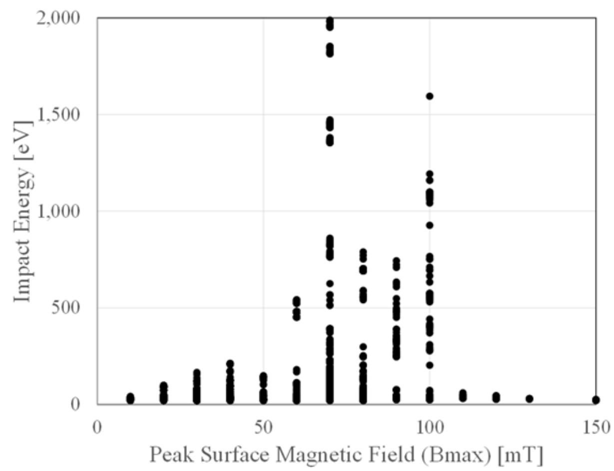

Figure 5: The impact energy of resonant particles over magnetic field.

CAVITY PREPARATION

Fabrication

The cavity is complete. Since the inner conductor has the peak surface field, the fabrication was directed to have the final weld elsewhere than the inner conductor area. Figure 6 shows the subassembly of inner conductor and end caps, and Figure 7 shows the assembled outer conductor.

Figure 6: Inner conductor subassembly.

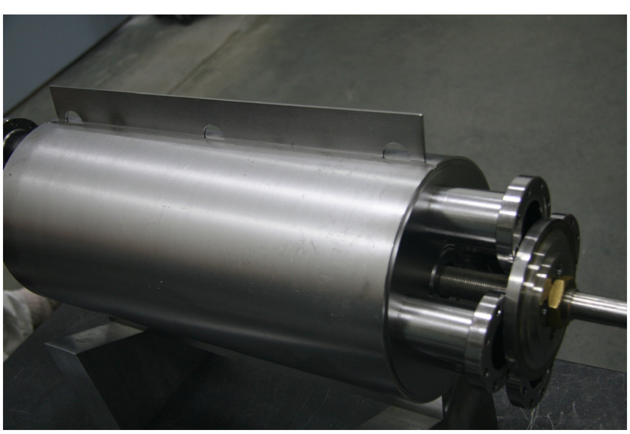

Figure 7: Outer conductor assembled and fitted for the final welding.

Test Preparation

The first test is planned to verify the cavity quality with a fixed input coupler. The cavity is prepared using a typical processing as follows however without the 120 °C bake:

- 150 µm bulk BCP,
- Heat treatment 10 hours at 600 °C,
- 10 µm light BCP,
- High pressure rinse, and then
- Clean room assembly.

The cavity assembled with a vacuum valve, input and pick up feedthroughs in the clean room is shown in Figure 8.

Figure 8: Prepared cavity for a cryogenic test in the clean room.

Variable Coupler

A variable coupler is necessary to test efficiently by maintaining critical coupling. While frequency and temperature are varying during the test a fixed coupler has the Q_{ext} range order of magnitude of two. If the variable coupler is not used, the cavity has to be warmed up and reassembled each time when the frequency or the temperature is changed. The variable coupler is built and verified for a seize- free motion. The coupler is a hook type coupling mainly to the magnetic field.

TEST PLAN

In summary, we propose to investigate the dependence of the surface resistance of niobium on temperature, RF field amplitude, and surface preparation and processing over a wide range of frequencies on the same surface. Prior to each cryogenic test, the cavity will have been subjected to different preparation steps including:

- Chemical polishing or electropolishing of various amounts,
- Low temperature bake,
- High temperature bake,
- Ambient magnetic field during cooldown,
- Plasma etching,

- Doping with impurities, and
- Plasma cleaning.

After each processing, the cavity will be tested at different temperatures ranging from 1.5 to 4.5 K, and different RF field magnitudes by changing the input power levels.

Under the reasonable assumption that a particular loss mechanism is uniformly distributed along the center conductor, then the same surface would be sampled for all the TEM modes, and the frequency dependence of that loss mechanism could be determined.

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