LOW POWERED RF MEASUREMENTS OF DIELECTRIC MATERIALS FOR USE IN HIGH PRESSURE GAS FILLED RF CAVITIES

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Abstract

The Helical Cooling Channel scheme envisioned for a Muon Collider or Neutrino Factory requires high pressure gas filled radio frequency cavities to operate in superconducting magnets. One method to shrink the radii of the cavities is to load them with a dielectric material. The dielectric constant, loss tangent, and dielectric strength are important in determining the most suitable material. Low powered RF measurements of the dielectric constant and loss tangent were taken for multiple purities of alumina and magnesium calcium titanate, as well as cordierite, forsterite, and aluminum nitride. Measurements of alumina were consistent with previously reported results. The results were used to design an insert for a high powered RF test that will include sending beam through the cavity.

INTRODUCTION

One muon cooling channel scheme, the Helical Cooling Channel (HCC), utilizes high pressure gas filled radio frequency (HPRF) normal conducting cavities placed within superconducting solenoids [1]. Current magnet technology dictates the radial size of these cavities be smaller than that of a pillbox cavity filled with hydrogen gas in the TM_{010} mode at 325 or 650 MHz [2]. Loading the cavities with a dielectric material is one solution with which to shrink the radii of the cavities. An experiment to determine the dielectric strength of 99.8% pure alumina has already been performed [3]. This paper will present an expansion of those results, including the dielectric constant and loss tangent of different purites of alumina, as well as magnesium calcium titanate (MCT), cordierite, forsterite, and aluminum nitride (AlN).

MATERIAL SELECTION

For a simple pillbox filled with a dielectic, the resonant frequency is

$$f_{nml} = \frac{c}{2\pi\sqrt{\mu_r\,\epsilon_r}}\sqrt{\left(\frac{p_{nm}}{R}\right)^2 + \left(\frac{l\,\pi}{L}\right)^2} \tag{1}$$

where c is the speed of light, μ_r and ϵ_r are the relative permeability and permittivity, respectively, and R and L are the radius and length of the cavity, respectively. Therefore in order to maintain a constant resonant frequency, one may add a dielectric in order to decrease the radius of the cavity. The loss tangent, $\tan\delta$, of a dielectric is related to the permittivity by

$$\epsilon = \epsilon_0\,\epsilon_r\,(1 - j\,\tan\delta) \tag{2}$$

where ϵ_0 is the permittivity of free space.

The choice of material is important in designing a cooling channel in that an appropriate amount of material, based on its permittivity, must be inserted in order to bring the radius of the cavity down while minimizing the energy dissipation in the dielectric material.

Samples of alumina of various purities were obtained from Morgan Advanced Ceramics [4], CoorsTek [5], and Accuratus [6]. Samples of cordierite, forsterite, and magnesium calcium titanate were obtained from Euclid Techlabs [7]. A sample of aluminum nitride was obtained from Sienna Technologies, Inc. [8]. Table 1 lists the quoted properties of each sample by the manufacturer. The dielectric constant and loss tangent of each were measured in order to design a realistic cooling channel dielectric insert.

Table 1: Dielectric Constant and Loss Tangent Values (including the Frequencies) Reported by Each Manufacturer. 1 = Morgan, 2 = Accuratus, 3 = CoorsTek, 4 = Euclid, 5 = Sienna

Material	**Man.**	**Purity (%)**	ϵ_r	$\tan\delta$ **(10^{-4})**	**Freq. (MHz)**
Alumina	1	94	9.04	6.2	1000
Alumina	1	96	9.20	4.4	1000
Alumina	1	97.6	9.00	3.0	1000
Alumina	2	97.6	9.00	3.0	1000
Alumina	1	99.5	9.30	1.4	1000
Alumina	3	99.5	9.70	1.0	1
Cordierite	4	N/A	4.6	<10	1300
Forsterite	4	N/A	6.64	<10	1300
MCT	4	N/A	20	<10	1300
MCT	4	N/A	35	<10	1300
AlN	5	95	8.5	10	1

DIELECTRIC SAMPLE TEST

A modified pillbox cavity was designed such that small rods or tubes of each dielectric material could be placed on a

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copper electrode on the axis of the cavity, and held in place with a copper plunger. Figure 1 shows the assembled cavity.

Figure 1: Dielectric sample test cavity fully assembled. Two copper endplates are held to a cylindrical body with 24 bolts. The samples are placed on a cylindrical copper electrode attached to the bottom endplate (not shown). A copper plunger (shown) is fastened in place to make contact with the sample and top endplate. Pickup probe ports are also shown.

Measurements of the resonant frequency and quality factor of the cavity with each sample were taken, and compared to simulations using Poisson Superfish [9]. The simulation model was benchmarked by measuring the frequency and Q dependence on plunger insertion depth of the empty (air filled) cavity. Figure 2 shows an example of one simulation of an alumina rod.

RESULTS

Measurements were made between 350 and 575 MHz. The results are given in Table 2.

The results for the alumina samples are shown in Figures 3 and 4. As the purity of the alumina increases, the variation in dielectric constant decreases (from about 1.2% to 0.2%), as impurities have a large impact on dielectric constant. Uncertainties introduced through the measurement and simulation also contribute. Variation in the loss tangent is larger at higher purity (3.3% up to 11%) due to the smaller perturbation in the cavity Q.

The results for the non-alumina samples are shown in Figures 5 and 6. The variation in the dielectric constant for forsterite is about 1.2% while that of MCT is about 1.1%. The variation in loss tangent for forsterite is about 19% while that of MCT is about 6.9%.

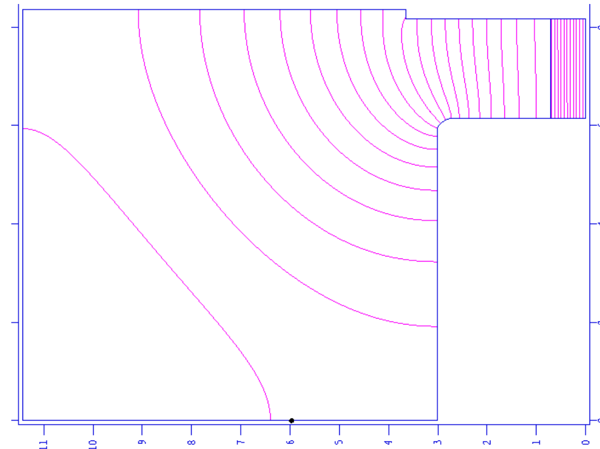

Figure 2: Superfish model showing the 2D cross section of one half of the cavity. The sample rod rests on the copper electrode, with the plunger inserted slightly to make contact. Field contour lines are shown. The dimensions are in centimeters.

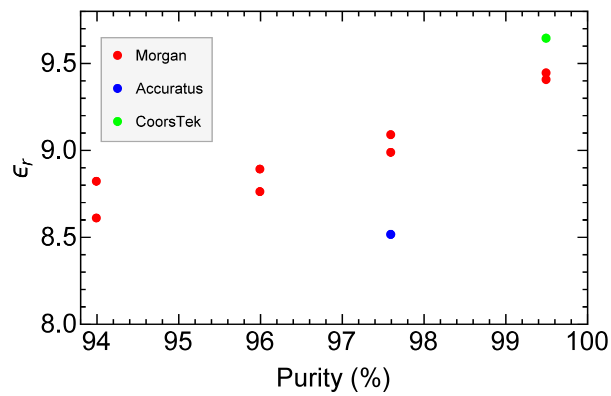

Figure 3: Dielectric constant vs. purity for all alumina samples. Two samples of each purity from Morgan were tested.

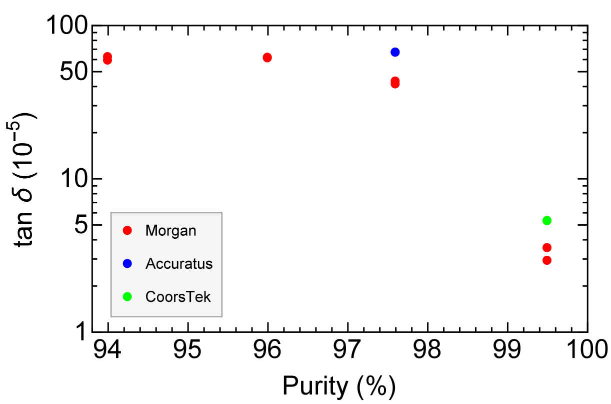

Figure 4: Loss tangent vs. purity for all alumina samples. Two samples of each purity from Morgan were tested.

CONCLUSION

Of the materials measured, only 99.5% alumina and the higher dielectric constant magnesium calcium titanate seem

Table 2: Results of the Dielectric Constant and Loss Tangent Values and Frequencies at Which They Were Measured

Material	**Manufacturer**	**Purity (%)**	Sample	ϵ_r	tan δ (10^{-4})	Frequency (MHz)
Alumina	Morgan	94	1	8.82	6.3	539
Alumina	Morgan	94	2	8.61	5.9	539
Alumina	Morgan	96	1	8.89	6.2	531
Alumina	Morgan	96	2	8.76	6.2	531
Alumina	Morgan	97.6	1	8.99	4.3	494
Alumina	Morgan	97.6	2	9.09	4.2	493
Alumina	Accuratus	97.6	1	8.52	6.7	568
Alumina	Morgan	99.5	1	9.41	0.36	461
Alumina	Morgan	99.5	2	9.45	0.29	461
Alumina	CoorsTek	99.5	1	9.65	0.53	429
Cordierite	Euclid	N/A	1	4.46	4.8	562
Forsterite	Euclid	N/A	1	5.20	1.8	577
Forsterite	Euclid	N/A	2	5.10	2.2	577
Forsterite	Euclid	N/A	3	5.15	1.9	578
Forsterite	Euclid	N/A	4	5.20	1.5	578
MCT	Euclid	N/A	1	18.9	1.4	354
MCT	Euclid	N/A	1	35.3	1.1	515
MCT	Euclid	N/A	2	35.5	1.1	515
MCT	Euclid	N/A	3	34.8	0.99	515
AlN	Sienna	95	1	8.58	141	520

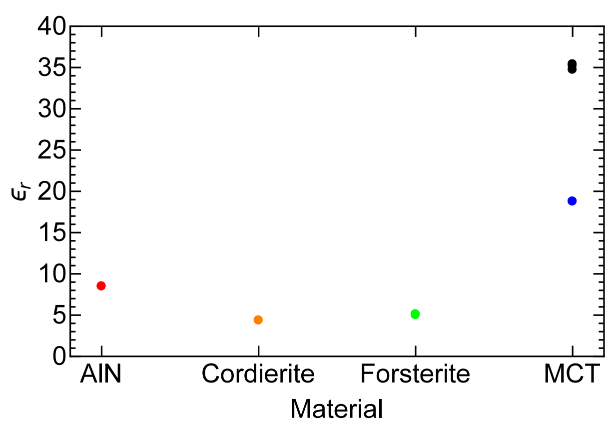

Figure 5: Dielectric constant for each non-alumina material. Multiple samples of forsterite and MCT (at two different purities) were tested.

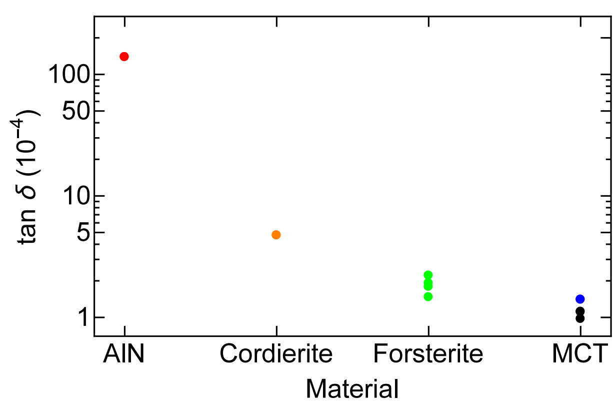

Figure 6: Loss tangent for each non-alumina material. Multiple samples of forsterite and MCT (at two different purities) were tested.

viable options for dielectric materials to be used in a muon cooling channel. 99.5% Alumina has the lowest loss tangent, however the dielectric constant of MCT is roughly six times larger, meaning one would need less material, which might negate the larger loss tangent. High purity alumina will be pursued in fabricating and testing a realistic cavity insert.

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