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Measurements of High-Temperature RF and Microwave Properties of Selected Aluminas and Ferrites Used in Accelerators

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Abstract

Modern accelerator design practice includes the use of alumina rf and microwave windows and high-quality ferrites in applications with ever-increasing requirements on power handling ability. Modeling studies of such designs are of increasing economic importance, but frequently are hindered by a lack of measured values of the ceramic loss factors. AECL has developed a system to measure the complex permittivity of small samples over a frequency range from 50 to 2450 MHz and up to 1000°C in temperature. Samples of rf window materials from several suppliers have been studied, with a view to relating the dielectric loss factor to the microscopic material properties. As well, the temperature dependence of the dielectric and magnetic loss factors of a few relevant ferrites were measured at selected frequencies.

I. INTRODUCTION

The challenge in modern accelerator design is to satisfy the increasing demands on performance and/or output without incurring the cost penalty usually associated with brute force techniques. New materials and new technologies are the main tools one uses, but to use them successfully requires increasingly sophisticated knowledge of their properties and interplay with each other. Metal oxide ceramics have a long history of use in accelerator systems, but improvements in their properties and development of new ceramics have opened up new design possibilities.

The 50 MHz cavities designed and constructed at Chalk River Laboratories [1] for the PETRA and HERA accelerator ring use high-quality ceramics in three separate applications to achieve the design requirements at reduced cost:

(1) A large alumina insulator spans the PETRA cavity accelerating gap, so that high vacuum is maintained in the beam line while the bulk of the cavity can operate in air. A cw rf voltage of 100 kV is maintained across a 200 mm gap using a 340 mm long, 155 mm diameter, 7 mm wall high-density alumina cylinder.

(2) A perpendicular-biased ferrite frequency shifting system allows electronic slewing of the cavity by 0.5 MHz (1%) at an average cavity input power of 6 kW. Use of the low loss TransTech G510 ferrite reduced the tuner average power dissipation up to 1000 W (0.5 W/cm^3 of ferrite), while simple interleaving of the ferrite rings with high thermal conductivity, hot isostatic press (HIP) sintered, beryllia rings provided adequate cooling.

(3) Unbiased ferrite with a specially chosen rf loss-versus-frequency characteristic was used in a simple higher order mode damping system.

Usually, the principles behind the use of these ceramics are well understood, but an engineered optimum design requires detailed knowledge of the rf properties, which often is not available. For example, two alumina insulator materials were tried in the PETRA cavity from different sources. Both had adequately low dielectric loss at room temperature, but in one material losses increased much more rapidly with temperature, and resulted in a marginal design, given the available cooling.

Studies have been initiated to measure the dielectric and magnetic properties of ceramics used in accelerator engineering design and to attempt to understand the mechanisms behind the rf loss processes in these materials.

II. A SYSTEM FOR MEASURING RF PROPERTIES USING THE CAVITY PERTURBATION METHOD

The Chalk River measurement system uses the traditional cavity perturbation technique, where a sample is introduced into either the electric or magnetic field region of a cavity and the change in frequency and quality factor, Q, are related to the permittivity and permeability of the sample. A small cylindrical sample, mounted in a thin-walled fused quartz tube, is heated to high temperature and rapidly inserted into a cooled rf cavity. As the sample cools, a Hewlett-Packard 8753 network analyzer, controlled via IEEE 488 interface by a personal computer, determines the resonant frequency and Q approximately every half second and accumulates the numbers in a file for later analysis. The data analysis assumes the validity of the general formalism of resonant cavity perturbation theory, but the absolute calibration relies on measurements at room temperature of known materials, on a detailed understanding of the full complex cavity perturbation theory formulation [2], and on comparisons with computer simulations using the fully complex version of SUPERFISH, which includes loss in materials.

Under the assumptions listed below, the exact resonant cavity frequency shift formula may be reduced to the following form

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Wesgo or Kyocera aluminas. All the loss tangent values at 1000°C were at least an order of magnitude larger than that measured for a high-purity, single-crystal sapphire calibration sample, demonstrating that impurity and/or grain boundary effects are still the determining factor in this temperature range.

IV. LOW-LOSS FERRITES FOR PERPENDICULAR BIAS APPLICATIONS

The ferrites recently proposed for electronic frequency slewing of high-power cavities are used in the perpendicular bias mode (magnetic bias field perpendicular to the rf magnetic field) to reduce magnetic losses. Trans Tech aluminum substituted YIG ferrites, G810 and G510, have been used in this mode because both their magnetic and dielectric losses are low. However, the increased amount of ferrite required to obtain a large frequency swing [3] means that the ferrite extends into regions of higher electric field, and more accurate estimates of the dielectric loss (and heating) are required.

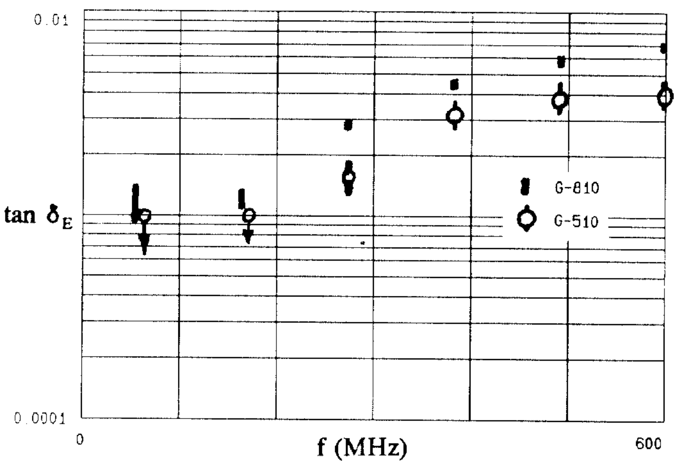

Figure 3. Measured room temperature (22°C) dielectric loss tangent of unbiased G810 and G510.

The dielectric constants of Trans Tech G510 and G810 were measured without magnetic bias (Figure 3). The presence of magnetic bias is thought to have no influence on the dielectric properties. A careful room temperature (22°C) measurement on unbiased G810 at 54.5 MHz gave $\epsilon_r' = 14.2 \pm 5\%$ and $\epsilon_r'' = 0.014 \pm 30\%$, for $\tan \delta_E = 1.0 * 10^{-3} \pm 30\%$. The G510 values were $\epsilon_r' = 13.3 \pm 5\%$ and $\epsilon_r'' \leq 0.012$, for $\tan \delta_E \leq 0.9 * 10^{-3}$. These values suggest a dielectric loss power dissipation of the order of 0.15 W/cm^3 in a 1 kV/cm, 50 MHz internal rf field. The value of ϵ_r' is constant over the frequency range in Figure 3, while the increase of the loss tangent with frequency clearly rules out electron conduction as the loss mechanism.

V. A HIGH-LOSS FERRITE FOR RF ABSORPTION APPLICATIONS

Ferrites have been used as rf absorbers in high-power tube resonators to suppress spurious resonances and higher order mode excitation. Recently, they have been used as a broadband absorber of all TE and TM modes above cutoff in a waveguide mode damper coupled to rf cavities in high-current storage rings. The ferrite must have a large loss factor for both electric and magnetic fields so that all mode distributions are attenuated.

Trans Tech F50 is specified to have excellent high-vacuum properties, a nominal Curie temperature of 390°C, and a nominal room temperature electrical resistivity of 25 ohm-cm. The permittivity and "scalar" permeability [2] were measured at 2.42 GHz under zero magnetic bias field (Figure 4). The lack of a defined bias field direction means that the measured value is an average over the presumably random orientations of the individual domain field directions. The phenomenon of the "effective" scalar rf permeability being less than unity over a region just below the Curie point is common to many ferrites in this frequency range.

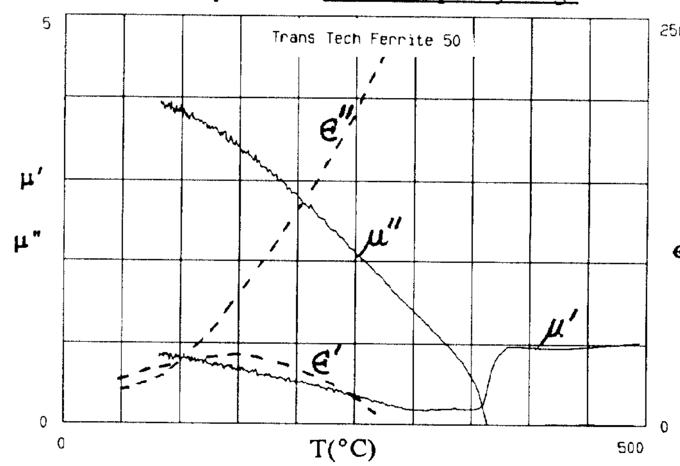

Figure 4. Measured permittivity and scalar permeability of Trans Tech F50 ferrite at 2.4 GHz.

Under the assumption that the dielectric loss is caused purely by free electron conduction, the room temperature value of ϵ_r'' may be used to deduce an effective resistivity for this sample of 37 ohm-cm.

V. REFERENCES

[1] L.W. Funk et al., "52 MHz RF Systems for PETRA II and HERA Proton Synchrotrons", Particle Accelerators, 29, pp. 71-76 (1990).

[2] R.M. Hutcheon et al., "A Technique for Rapid Scoping Measurements of RF Properties up to 1000°C", Electromagnetic Energy Reviews, 2, 46 (1989).

[3] R.L. Poirier, T.A. Engren, C. Haddock, "A Perpendicular AC Biased Ferrite Tuned Cavity for the TRIUMF Kaon Factory Booster Synchrotron", Proceedings of the 2nd European Particle Accelerator Conference, 1, 988 (1990).

$$\frac{\Delta f}{f} + j \cdot \Delta\left(\frac{1}{2Q}\right) \approx - \frac{\chi_e}{(1+\chi_e F_{sh})} \cdot \frac{V_s}{V_c} \cdot A \qquad (1)$$

where χ_e is the complex relative susceptibility (dimensionless), F_{sh} is a sample shape factor (real, dimensionless), V_s and V_c are the sample and cavity volumes, respectively, and A is a dimensionless real constant depending only on the shape of the cavity and the shape of the unperturbed fields. The assumptions are:

(a) The sample is located in a region of uniform field.

(b) The sample shape is an ellipsoid of rotation.

(c) The stored energy in the sample is small compared to that stored in the rest of the cavity.

It may be shown that relation (1) applies to non-ellipsoidal shapes when empirical values of A and F_{sh} are used. This approximation has been checked with full complex numerical calculations and found to be accurate to $\pm$ 3% for sample length to diameter ratios down to 3.5:1.

III. LOW-LOSS ALUMINAS FOR RF AND MICROWAVE APPLICATIONS

Initial studies of loss mechanisms were done on samples from four ceramics that had been purchased and used as rf and microwave windows (Table 1). All are high-purity aluminas and have low dielectric loss tangent ($\tan \delta = \epsilon''/\epsilon'$) at room temperature. Structural studies were done both of fracture surfaces and of polished and thermally etched faces. As well, energy dispersive X-ray analysis (EDX) was used to give an indication of the type and amount of impurities (assumed to be sintering aids). The dielectric constants were measured (Figure 1) using 12 mm long, 3.5 mm diameter specimens that had been diamond-core drilled, cleaned and held in air at 1000°C for 2 hours in high-purity alumina boats.

Table 1

Measured Properties of Four RF Window Materials

Specimen	Additives	Grain Size	Pores	Cryst.Str.	tan δ
Wesgo AL-995	< 0.5%	Aver. 25μm Range 5-60	S. 1-3 μm	α -	≤ 1x10^{-4} 25°C 2x10^{-4} 300°C 50x10^{-4} 1000°C
Degussit AL23	< 0.5%	Aver. 30μm Range 3-80	S. 1-3 μm	α -	≤ 1x10^{-4} 25°C 3x10^{-4} 300°C 17x10^{-4} 1000°C
Kyocera	< 0.5%	Aver. 40μm Range8-120	4 μm .5-30	α -	≤ 1x10^{-4} 25°C 3x10^{-4} 300°C 56x10^{-4} 1000°C
Coors AD 995	1< Ca < 2% 0.5< Mg < 1%	Aver. 15μm Range 5-40	S. 1-3 μm	95% α - spinel	≤ 1x10^{-4} 25°C 11x10^{-4} 300°C 37x10^{-4} 1000°C

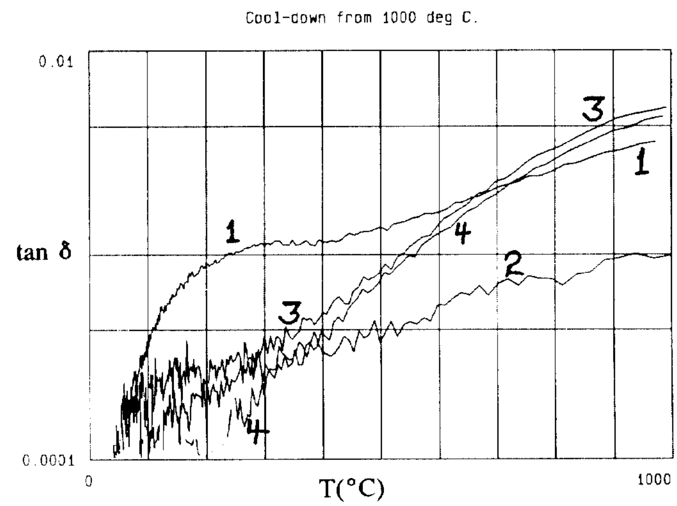

Figure 1. Measured loss tangent at 2.4 GHz for (1) Coors AD-995, (2) Degussit AL-23, (3) Kyocera, (4) Wesgo AL-995.

The Coors loss tangent temperature dependence is clearly different from the others (Figure 1), rising steeply above room temperature and peaking (or leveling) around 300°C. The same temperature dependence occurs at lower frequencies (Figure 2) and will lead to thermal runaway above specific high rf power levels. The frequency dependence (Figure 2) clearly demonstrates that electron conductivity, which would give $\epsilon'' \propto f^{1}$, is not the loss mechanism. The spinel structure, evident in the Coors EDX spectrum, is the only clear difference between the materials, and will be studied as a possible mechanism of low-temperature loss in aluminas.

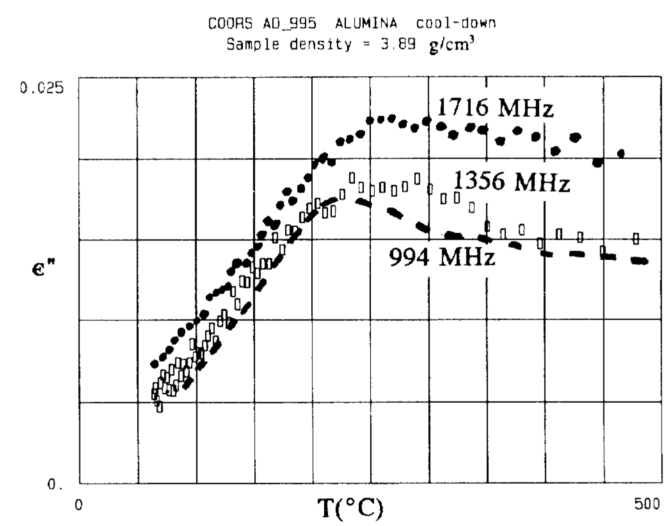

Figure 2. Measured absorptive part of the permittivity for Coors AD-995.

The high-temperature loss tangent appears unrelated to the previously mentioned low-temperature loss, for at 1000°C the Coors material has a lower tan δ value than either the