ABSTRACT

The RF window vacuum seals on the 400-GeV Fermilab accelerating RF cavities are very large circular cylinders of alumina. The cavities were first installed with seals of 94% purity Al2O3. Several of these seals failed in high-power operation due to dielectric heating. Higher purity ceramics (99.5% Al2O3) have been obtained and are now being installed. The complex permittivity of both types of ceramic has been measured in a TM010 mode test cavity ten-inches high and eight feet in diameter. Frequency shift and Q shift data have been analyzed by perturbation analysis and by computer programs. Results confirm that the higher purity ceramics have a loss tangent a factor of five better than the original seals. Some high-power operational test results are also presented.

INTRODUCTION

At the time (1970) the main synchrotron RF accelerating cavities were built, ceramic manufacturers could fabricate cylinders larger than 4-inch diameter using alumina of only 94% or less purity. There were some misgivings that these would not be able to withstand the RF power in the cavity. In the Fall of 1972 the first ceramic cracked, destroying the vacuum in the RF straight section which confirmed earlier suspicions. A study using computer solutions of Helmholtz's equation revealed that the power dissipation in the ceramic was enough to cause a thermal runaway at the location of the actual crack.

In 1971, just before the last of the 16 cavities were finished, several 97.5% alumina were purchased and two were installed in one of the last cavities. By late 1972 several manufacturers thought they could make such cylinders of 99.5% alumina using new higher pressure hydrostatic presses to form material with very little binder. Presently only three of the fifteen RF cavities used for beam acceleration have the original 94% ceramics, three have 97.5% and nine have 99.5%. The ceramics are exchanged and several mechanical modifications are made (additional water cooling and welding several RF current-carrying joints) in three to four weeks time. By July of this year all the cavities are finished, several 97.5% alumina were purchased and were installed in one of the last cavities.

To verify manufacturers specifications, and unit to unit consistency, the complex permittivity of all the ceramics was measured.

TEST CAVITY DESCRIPTION

An 8 x 8 foot octagonal cavity ten-inches high was built using standard 4 x 8 foot plywood sheets and lined with copper sheet soft-soldered together. This cavity resonates in the TM010 mode about 90 MHz. A considerably larger cavity would be needed for testing the ceramics at the actual accelerating frequency of 53 MHz, but the permittivity doesn't change much in this frequency range, so an eight-foot box was considered unwieldy enough. A hole large enough to insert a ceramic was cut in the top and a cover with clamp bolts was fitted over the ceramic.

The Q for a perfect copper cavity operating at 90 MHz in the TM010 mode is about 30,000. Typical Q for the empty test cavity during ceramic measurements is 21,000. The highest measured Q was 24,500. The top of the cavity is held on with wood screws and these make the connection between the copper lining of the top and sides. Soft-soldering this connection would improve the Q but it was not considered necessary, since the difference between loaded and unloaded Q is easily measured.

PERTURBATION THEORY APPROXIMATION

Loading a cavity with a dielectric shifts the frequency and a perfect TM010 cylindrical cavity with a post at the center:

\[ \Delta f = \frac{(\varepsilon' - 1)}{2} \frac{V_{\text{cer}}} {V_{\text{cav}}} f_{\text{cav}} \]  

or \[ \varepsilon' = 1 + 2 \frac{V_{\text{cav}}}{V_{\text{cer}}} \Delta f / f_{\text{cav}} \]  

Similarly, adding a lossy dielectric changes the Q and the loss index can be found:

\[ \varepsilon'' = \left( \frac{1}{Q_{\text{cav}}} - \frac{1}{Q_{\text{cer}}} \right) \frac{V_{\text{cav}}}{V_{\text{cer}}} \]  

Since the electric field does not change much from the center to the radius of the ceramic:

\[ \varepsilon'' (r = \text{7.122'}) = J_2 (0.382) / J_2 (0) = 0.9655 \]  

The cylinder perturbs the cavity approximately the same way as a post at the center and these equations for two dielectric regions can be used instead of the exact three region geometry of a hollow cylindrical dielectric.

MEASUREMENTS

Four types of ceramic cylinders were measured: 94% Coors, 97.5% Wesgo, 99.5% Wesgo, and 99.5% Coors.

Table I shows average values for the number, n, measured. Typical variations in \( \varepsilon' \) are ±1% and \( \varepsilon'' \) are ±14%.

Temperatures of the ceramic seals under RF power conditions were measured for various power levels and are shown in the graph. Under no power conditions the seals are about 70°F, the temperature of the RF cavity cooling water.

To check the perturbation method, a computer program was written to solve the field equations inside the cavity. In the two regions outside the ceramic, the solution to the wave equations are assumed to be the same as for an empty cavity. Inside the ceramic the solution is approximated by a Taylor series expansion modified by a dielectric with \( \varepsilon_r \geq 1 \). It is given by:

\[
E' = 2A_o \left( J_0 (KA) - \frac{K}{\varepsilon_r} J_1 (KA)(r-A) \right)
\]

\( A < r < B \):

\[
H_z = A_o \left( J_1 (KA) + \frac{K}{\varepsilon_r} \left( J_0 (KA) - \frac{J_1 (KA)}{KA} \right)(r-A) \right)
\]

where \( \varepsilon' \) is the real part of the relative dielectric constant of the ceramic, \( \alpha = \varepsilon_0 / \varepsilon_r \), \( K \) is the propagation vector, \( A_o \) is a constant, and \( J_0 \) and \( J_1 \) are Bessel functions.

The boundary conditions at \( r = A, r = B \) and \( r = \text{effective outer radius} \) were solved, giving three equations involving the relative dielectric constant and the propagation vector. A trial \( \varepsilon' \) was assumed and then the boundary conditions were iterated until the change in \( K \) was less than a certain level. This \( K \) was then used to determine a new \( \varepsilon' \) which in turn was put into the boundary conditions and looped over to get a new \( K \). This process was repeated until both quantities were determined to some specified degree of accuracy. Finally \( \varepsilon' \) was determined from the exact formula:

\[
\omega = \frac{\varepsilon_0 (\varepsilon' - 1) \int E (E^* \delta t \text{dielectric})}{2 \varepsilon_0 (E E^* \delta t \text{total volume})}
\]

where \( \omega \) and \( \Delta \omega \) are the original frequency and change in frequency, \( \varepsilon_0 \) is the electric field with no ceramic, \( E \) the field with ceramic, and \( dr \) a differential volume. The denominator was approximated as:

\[
2\varepsilon_0 \int |E|^2 dt
\]

with

\[
E = \alpha \left[ J_0 (KA) + \frac{1}{\varepsilon_r} \left( J_0 (KA) - \frac{J_1 (KA)}{KA} \right)(r-A) \right]
\]

\( K, A_0, \) and \( A_1 \) determined using the calculated value of \( \varepsilon' \). The entire process was then repeated until a self-consistent solution was obtained.

To find the imaginary part of the relative dielectric constant, \( \varepsilon'' \), first \( Q_0 (\varepsilon' = 1, K = K_0) \) was calculated from \( Q_0 = \omega_0 P_0 / E_0^2 \) with \( \omega_0, \omega_0, P_0 \) being original frequency, stored energy, and power loss in walls. From this and the measured shifted frequency and bandwidth, the surface resistance of the walls was found. Then the two parts of the actual \( Q \) were calculated from:

\[
Q = \left( \frac{1}{Q_{\text{lossy}}} + \frac{1}{Q_{\text{non-lossy}}} \right)^{-1}
\]

This was then compared to the final frequency and bandwidth and solved for \( \varepsilon'' \).

Tests run on materials having a known dielectric constant show these calculations to yield an accuracy of approximately \( \pm 2\% \).

Comments

In the temperature graph there are two factors at work; lower loss ceramic material and modified corona rolls at each end of the ceramic which distributes the electric fields in the accelerating cavity more evenly than the original corona rolls. There corona rolls also shield the vacuum weld flange from the electric field.

The apparently large variation (\( \pm 14\% \)) of the imaginary part \((\varepsilon'')\) of the permittivity can be due to several possible causes; variation in the raw alumina, variation in the binder material used in the pressing process, differences in firing environment from batch to batch and differences in brazing process from piece to piece.

The data are for cylinders which have been metalized on the ends and brazed to a vacuum weld flange. The pieces are held together in the brazing oven by a graphite fixture and some graphite and residue from tape used to position the graphite are often deposited on the ceramic. In the worst case, \( \varepsilon'' \) was 290, about six times the average of 56.

CONCLUSION

Table III lists manufacturers specifications for 99.5% alumina and average measured values. The differences are probably due to the manufacturers conservative estimates rather than any sophistication or better accuracy in the methods we used.

REFERENCES

2. Western Gold and Platinum Co.; Belmont, California Coors Porcelain Co.; Golden, Colorado
5. Pyro-Met, Inc., San Carlos, California
### TABLE I
Average Measured Complex Permittivity for Various Size and Purity Alumina Cylinders

<table>
<thead>
<tr>
<th></th>
<th>ε'</th>
<th>ε''</th>
<th>tan δ</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>94 Coors</td>
<td>3</td>
<td>8.79</td>
<td>314 x 10^{-5}</td>
<td>17 x 10^{-5}</td>
</tr>
<tr>
<td>97.6 Wesgo</td>
<td>3</td>
<td>9.21</td>
<td>135</td>
<td>14.8</td>
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<tr>
<td>99.5 Wesgo</td>
<td>10</td>
<td>9.62</td>
<td>71.9</td>
<td>7.47</td>
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<td>(3/8&quot; wall)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>99.5 Wesgo</td>
<td>16</td>
<td>9.40</td>
<td>56.4</td>
<td>6.37</td>
</tr>
<tr>
<td>(2/2&quot; wall)</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>99.5 Coors</td>
<td>2</td>
<td>9.56</td>
<td>42.8</td>
<td>4.46</td>
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### TABLE II
Comparison of Perturbation (p) and Computed (c) Calculations for Two Typical Ceramic Cylinders

<table>
<thead>
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<th>CASE I</th>
<th>CASE II</th>
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<tbody>
<tr>
<td>p c</td>
<td>p c</td>
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<tr>
<td>ε'</td>
<td>8.74 8.77</td>
</tr>
<tr>
<td>10^5 ε''</td>
<td>294 318</td>
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<tr>
<td>10^5 tan δ (ε''/ε')</td>
<td>33.6 36.2</td>
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### TABLE III
Comparison of Manufacturers Specifications With Average Measured Values for 99.5 Alumina

<table>
<thead>
<tr>
<th></th>
<th>ε'</th>
<th>ε''</th>
<th>tan δ (ε''/ε')</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wesgo Measured</td>
<td>9.45</td>
<td>150 x 10^{-5}</td>
<td>16.5 x 10^{-5}</td>
</tr>
<tr>
<td>Coors Measured</td>
<td>9.7</td>
<td>56.4</td>
<td>6.37</td>
</tr>
</tbody>
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**CERAMIC VACUUM SEAL**

Temperature vs Power Dissipated in RF Cavity