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DIELECTRIC PROPERTY MEASUREMENTS ON LARGE ALUMINA VACUUM SEALS USED ON FERMILAB ACCELERATOR RF CAVITIES

J. F. Bridges, D. E. Johnson and J. E. Griffin
Fermi National Accelerator Laboratory*
Batavia, Illinois

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 Al_2O_3. Several of these seals failed in high-power operation due to dielectric heating. Higher purity ceramics (99.5% Al_2O_3) have been obtained and are now being installed. The complex permitivity of both types of ceramic has been measured in a TM_{010} 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 solution of Helmholtz' equation revealed that the power dissipation in the ceramic was enough to cause a thermal runaway at the location of the actual crack.[1]

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[2] thought they could make such cylinders of 99.5% alumina using new higher pressure hydrostatic presses to form material with very little binder (≈ ½%).

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 cavities are removed from the accelerator tunnel, 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 scheduled to be "re-cycled" and three additional cavities with 99.5% ceramics will be installed to increase redundancy and to allow accelerator operation at a higher repetition rate.

To verify manufacturers specifications, and unit to unit consistency, the complex permitivity of all 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 TM_{010} 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 permitivity 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 TM_{010} 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 for a TM_{010} cylindrical cavity with a post at the center:[3]

$$\Delta f = \frac{(\varepsilon' - 1)}{2\, J_1^2\,(ka)} \; \frac{V_{CER}}{V_{CAV}} \; f_{CAV} \qquad (1.$$

$$\text{or} \quad \varepsilon' = 1 + 2\, J_1^2\,(ka) \; \frac{V_{CAV}}{V_{CER}} \; \frac{\Delta f}{f_{CAV}} \qquad (2.$$

Similarly, adding a lossy dielectric changes the Q and the loss index can be found:[4]

$$\varepsilon'' = \left(\frac{1}{Q_{CAV}} - \frac{1}{Q_{CER}} \right) J_1^2\,(ka) \; \frac{V_{CAV}}{V_{CER}} \qquad (3.$$

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

$$\frac{E_{max}\ (r = 7.125'')}{E_{max}\ (\ r = 0)} = \frac{J_0\ (0.382)}{J_0\ (0)} = 0.9655 \qquad (4.$$

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 ε' are ±1% and ε'' 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.

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COMPUTER PROGRAM SOLUTION

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:

$$E_2 = \alpha A_o \left[J_o(KA) - \frac{K}{\varepsilon'} J_1(KA)(r-A) \right]$$

$$A<r<B: \qquad H_2 = A_o \left\{ J_1(KA) + \frac{K}{\varepsilon'} \left[J_o(KA) - \frac{J_1(KA)}{KA} \right] (r-A) \right\} \qquad (5.$$

where ε' is the real part of the relative dielectric constant of the ceramic, $\alpha = \sqrt{\mu_o/\varepsilon_o}$, K is the propagation vector, A_o is a constant, and J_o and J_1 are Bessel functions.

The boundary conditions at r = A, r = B and r = effective outer radius were solved, giving three equations involving the relative dielectric constant and the propagation vector. A trial ε' was assumed and then the boundary conditions were interated until the change in K was less than a certain level. This K was then used to determine a new ε' 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 ε' was determined from the exact formula:

$$\frac{\Delta\omega}{\omega} = \frac{\varepsilon_o(\varepsilon'-1)\int E\, E_o^* \, d\tau_{\text{dielectric}}}{2\varepsilon_o \int E\, E_o^* \, d\tau_{\text{total volume}}} \qquad (6.$$

where ω and $\Delta\omega$ are the original frequency and change in frequency, ε_o is the electric field with no ceramic, E the field with ceramic, and $d\tau$ a differential volume. The denominator was approximated as:

$$2\varepsilon_o \int |E|^2 \, d\tau$$

$$\text{with} \quad E = \alpha \left\{ A_o J_o(Kr) + A_o \left[J_o(KA) - K\, J_1(KA)(r-A) \right] + A_1 J_o(Kr) + A_2 Y_o(Kr) \right\} \qquad (7.$$

and K, A_1, and A_2 determined using the calculated value of ε'. The entire process was then repeated until a self-consistent solution was obtained.

To find the imaginary part of the relative dielectric constant, ε'', first $Q_o(\varepsilon' = 1, K = K_o)$ was calculated from $Q_o = \omega_o W_o / P_o$ with ω_o, W_o, P_o 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:

$$Q = \left(1/Q_{\text{lossy}} + 1/Q_{\text{non-lossy}} \right)^{-1} \qquad (8.$$

This was then compared to the final frequency and bandwidth and solved for ε''.

Tests run on materials having a known dielectric constant show these calculations to yield an accuracy of approximately ½%.

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.[1] There corona rolls also shield the vacuum weld flange from the electric field.

The apparently large variation (± 14%) of the imaginary part (ε'') of the permitivity 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.[5] 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, ε'' 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

1. Analysis of NAL Main Ring Ceramic Bushing; W. Neugebaur, June 1973, General Electric Co., Microwave Tube Operation.

2. Western Gold and Platinum Co.; Belmont, California Coors Porcelain Co.; Golden, Colorado

3. Fields and Waves in Modern Radio; S. Ramo and J. R. Whinnery, 2nd ed Wiley, 1953 10:13 p.445

4. Theory of Waveguides and Cavities; R. A. Waldron Maclaren & Sons, Ltd., London 1967, p. 93

5. Pyro-Met, Inc., San Carlos, California

TABLE I

Average Measured Complex Permittivity for Various Size and Purity Alumina Cylinders

	n	ε'	ε"	tan δ	Q
94 Coors	3	8.79	314×10^{-5}	37×10^{-5}	2,700
97.6 Wesgo	3	9.21	135	14.8	6.760
99.5 Wesgo (3/8" wall)	10	9.62	71.9	7.47	13,400
99.5 Wesgo (1/2" wall)	16	9.40	56.4	6.37	15,700
99.5 Coors	2	9.56	42.8	4.46	22,400

TABLE II

Comparison of Perturbation (p) and Computer (c) Calculations for Two Typical Ceramic Cylinders

	CASE I		CASE II	
	p	c	p	c
ε'	8.74	8.77	9.32	9.34
10^5 ε"	294	318	54.2	63.5
$10^5 \tan \delta \left(\frac{\varepsilon''}{\varepsilon'}\right)$	33.6	36.2	5.8	6.8

TABLE III

Comparison of Manufacturers Specifications With Average Measured Values for 99.5 Alumina

	ε'	ε"	$\tan \delta \left(\frac{\varepsilon''}{\varepsilon'}\right)$
Wesgo	9.45	150×10^{-5}	16.5×10^{-5}
Measured	9.40	56.4	6.37
Coors	9.7	250	25.7
Measured	9.56	42.8	4.46