Transverse Impedance Measurements of Prototype Cavities for a Dual-Axis Radiographic Hydrotest (DARHT) Facility*

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I. INTRODUCTION

We have reported coupling impedance measurements on pillbox cavities [1] that were performed in preparation for studying the dual-axis radiographic hydrotest facility (DARHT) cavities. Both beadpull and wire methods were explored. From the study, we concluded that wire methods could be used to accurately measure the transverse impedance of the DARHT cavities. This report describes the results of wire measurements of several prototype DARHT cavities. References 1-2 describe in detail the measurement method.

The TM_{1n0} (or dipole) modes are deflecting modes of cavities, and the transverse coupling impedance is a measure of how efficiently the beam interacts with these modes. In this paper we will use the following definition of transverse impedance (expressed in the mks system of units):

$$Z_\perp = \frac{cQ[\int B_y dz]^2}{2U}$$

where c is the speed of light, Q is the quality factor, B is the magnetic field, z is the direction along the beam axis, and U is the stored energy in the cavity.

II. MEASUREMENTS

Figure 1 is a diagram of the three DARHT cavity models. The cell geometry for MOD0 is similar to a design used at Lawrence Livermore National Laboratory (LLNL) [3]. The insulator was slanted at approximately the Brewster angle to enhance the flow of rf to the ferrites, and the cavity had a corner that reflected the wave back to the ferrites. Rexolite, with a low dielectric constant close to that of the oil, was used to minimize rf reflections and to maintain a good high-voltage field profile. For all geometries AMOS [4,5] code predictions guided the designs, and the fields in the vacuum were kept below 200 kV/cm for a 250 kV accelerating voltage. The next design, MOD1, used resistive material and a smaller insulator aperture to lower the impedance and thus to improve the match at the insulator. In the MOD2 design we attempted to have a waveguide below cutoff for the TM_{110} mode and to hide the insulator from the beam. A partial ring of ferrite for the beam return current to flow through was added to absorb the TM_{120} mode. The cells are powered by two 50-Ω cables, each terminated by a 77-Ω resistor just before the drive rods enter the cell. Early in the measurements we realized that the drive rods and terminating resistors strongly affected the cavity impedance, so three types of resistors were tested on each cell. Two resistor designs, one with a carborundum resistor concentric to and enclosing the drive line and the other a stacked resistor parallel to the drive line, were built with little regard for rf considerations. The third design, a coaxial resistor in an exponential horn, was designed and tested on the assumption that its good rf properties might lower the cavity impedance. Because the rf penetration into the ferrite at the frequencies of the TM1n0 modes is only a few centimeters, the test cavities can be much shorter than an actual induction cell.

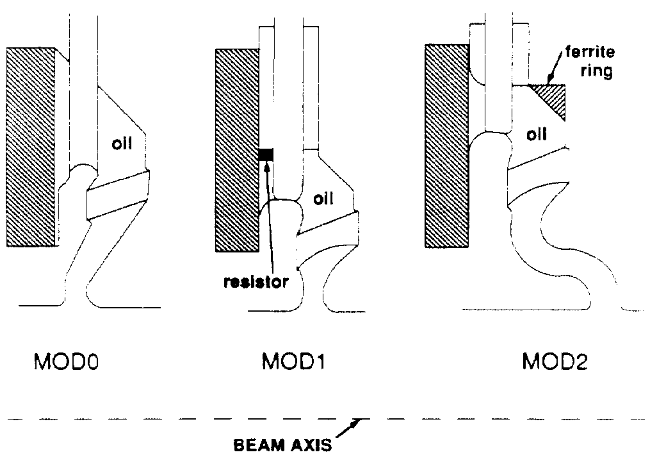

Figure 1. Geometry of three prototype DARHT cells. The three cells have cylindrical geometry except where the drive rods enter at the top and bottom of the cavity.

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A. *MOD0 with Ferrites Removed*

We initially measured the cavity impedances with the ferrites removed. We modeled the cavity with MAFIA, a 3-D code that solves Maxwell's equations on a rectangular mesh. Four of the modes have dipole characteristics in the beam tube and a sextupole field configuration in the body of the cavity. This means that modes are being mixed in the cavity. URMEL-T (a 2-D code which also solves Maxwell's equations) predicted a TM_{120} mode at 1002 MHz and a TM_{310} mode at 1015 MHz. Each of these have two degenerate modes. The introduction of radial asymmetries in the cavity couple these four modes together, resulting in four mixed modes. These four mixed modes were predicted by MAFIA and closely matched the frequency and field distributions in the cavity. Table I shows the results of this measurement.

Because of MAFIA's rectangular mesh, parts of the geometry are coarsely reproduced. The TM_{310} mode has its strongest electric field in the region of the rim that connects to the drive rod. This rim is very poorly represented in the MAFIA model. Therefore it is not surprising that the impedances calculated for these mixed modes do not correspond as closely as for the TM_{110} modes.

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Table I.
Measurement Results of DARHT Cavity
with Ferrites and Drive Rods Removed

	MAFIA		Measured	
	f(MHz)	$T^2Z_\perp/Q$ (Ω/m)	f(MHz)	$T^2Z_\perp/Q$ (Ω/m)
TM110 (H)	403	181	418	177
TM110 (V)	431	199	445	195
TM120/310 (H)	811	42	851	102
TM120/310 (V)	956	7	966	13
TM120/310 (H)	966	38	976	51
TM120/310 (V)	978	57	980	61

(H) refers to measurements in the plane of the drive rod mounts.
(V) refers to measurements in the normal plane.

B. MOD0, MOD1 and MOD2

1. AMOS Calculations

Figure 2 shows measured and calculated impedances for the three cavities with the rods removed. Both MOD0 and MOD2 were measured with and without oil, and MOD1 was measured in air only. The measured impedances plotted are $Z_\perp$ in the plane perpendicular to the plane containing the drive rods. The reason for this is that asymmetries in the cavities occur in the plane of the drive-rod mounts; therefore, the modes oriented such that the rods displace negligible field are better represented by the 2-D code. Figure 3a shows two calculated values. Originally AMOS contained a pure wave boundary condition ($Z_{boundary} = E_{||}/H_{||}$) to simulate the ferrites but has been modified to allow material with magnetic conductivity σ_m [5]. The data shown in Fig. 3b-c are calculated using only the modified version of AMOS.

Errors in the measurement are primarily due to three sources. First, the presence of the wires in the cavity locally changes the fields, thus changing the cavity impedance. This effect should be small (probably on the order of 10% or less) for the case of the DARHT cavities, because the beam pipe diameter is much greater than the wire diameter. The second source of errors is the calibration itself. The measured transverse impedance is calculated from

$$Z_\perp = \frac{2Z_0c(1 - S_{21})}{\omega\Delta^2 S_{21}}$$

where Z_0 is the characteristic impedance of the transmission line formed by the beam pipe and wires, Δ is the distance between the wires, and S_{21} is the transmission through the cavity. When S_{21} is large (as is the case for small impedances), 1- S_{21} is small, making a 1% uncertainty in S_{21} result in large errors. The third source is uncertainty in the spacing between the wires, Δ. Since the transverse impedance is as $1/\Delta^2$, uncertainties in Δ can contribute strongly to measurement errors. (The change in Z_0 due to changes in Δ is small by design.) The error bars indicated in Fig. 3 have been calculated as the square root of the sum of the squares of the expected maximum values of these three contributions. Measurements indicate that the wire spacing is constant (and known) to 2% and the calibration is kept within +/- 1%.

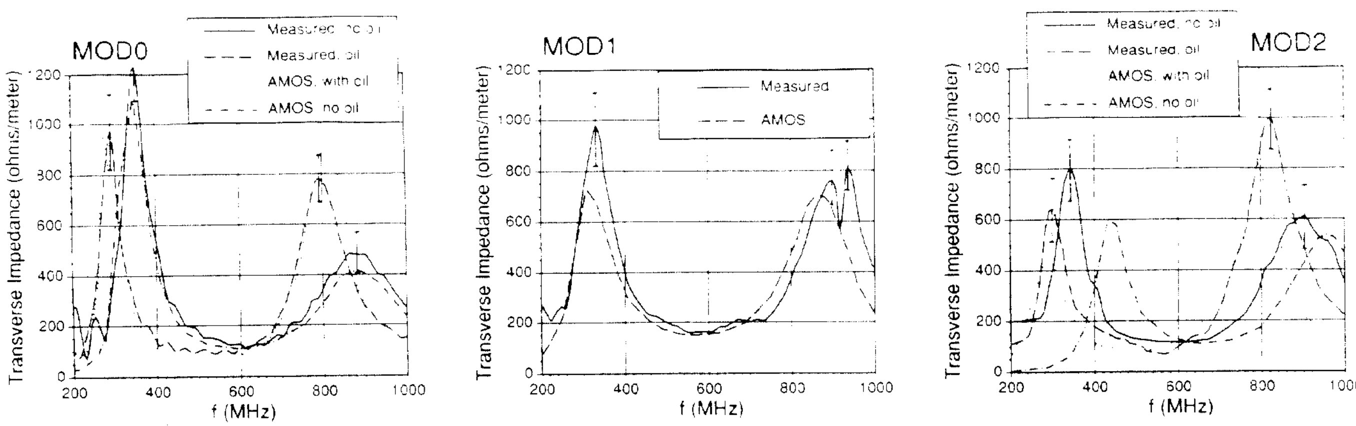

Figure 2. Comparison of measured impedances vs. AMOS predictions.

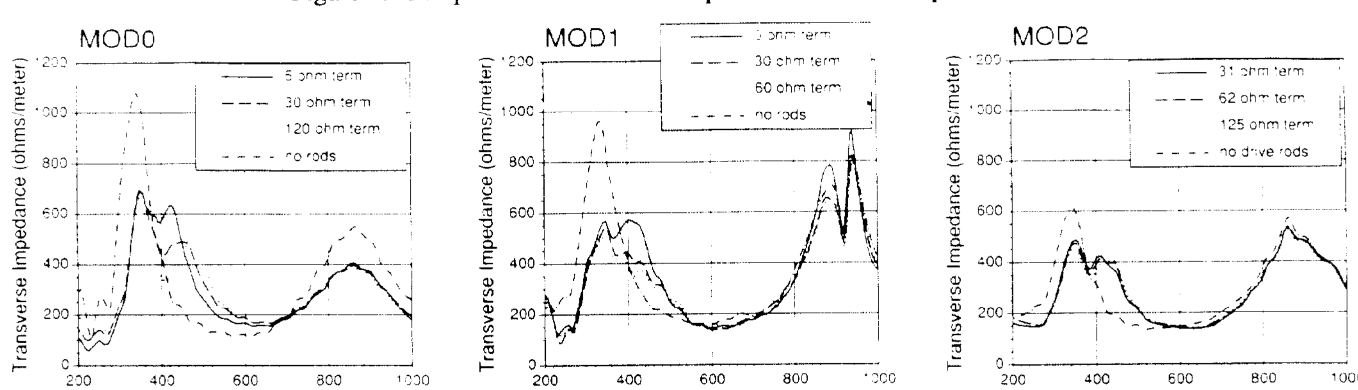

Figure 3. Effect of various rod terminations on cavity impedances.

2. Measurements With Drive Rods in Place With Various Terminations

Figure 3 shows plots of impedances measured without drive rods, and with the rods in place and terminated in various resistances. These resistors were built from two concentric rings with many parallel high-frequency resistors mounted radially. The differences in measured impedances between different terminating resisitances on the rods is generally much less than the difference between having the rod in and terminated (with anything) and having no rods in at all. In almost all cases the rods lower the mode impedances by coupling power out of the cavity.

These plots and all succeeding ones are presented as the average of the impedances measured in the planes parallel and normal to the plane containing the drive rods. The reason for this is that, because of the mode splitting caused by the drive rods, the total impedance seen by the beam can be reduced by placing half of the drive cells in one orientation (i.e., drive rods positioned horizontally) and the other half of the drive cells positioned with the drive rods vertical.

3. Measurements With Compensation Cans

The cavities must operate with the drive lines in place and loaded with compensating resistors that serve a dual purpose. First, the compensating resistor box must provide a relatively low shunt impedance in parallel with the cavity so that the drive line sees a constant input impedance in the presence of beam current and ferrite bias changes. Secondly, it is desirable that the compensating resistors provide an optimum termination to the drive rods as seen by the cavity so that the cavity modes are optimally damped. As expected, the rf resistor appeared superior. However, when the cans were mounted on the cavities and their drive lines terminated (Fig. 4), there were very small differences in the cavity impedances with different compensation cans. This finding is consistent with the results in Section 2.2.2, where the drive rods were terminated in simple resistors.

III. CONCLUSIONS

Simulations using BREAKUP [6], a code written by George Caporaso of LLNL using the beam breakup theory developed by Neil, Hall and Cooper [7], indicated that cavity impedances equal to or less than 670 W/m are acceptable for the DARHT cells. The cavity measurements indicate that we are close to that goal. In addition to the results presented, we measured impedances in MOD0 while biasing the ferrites by driving a dc through the rods. We found that the impedances were further reduced by as much as 20% when the ferrites were biased by 550 A. When this reduction is taken into consideration, we are confident that MOD0 and MOD2 will perform satisfactorily for beam breakup, although MOD2 looks slightly better and has the added benefit of shielding the insulator from the line of sight of the beam.

Although the different compensation resistors vary greatly when measured alone, when mounted on the cavities there is little difference between them. Therefore it would be reasonable to use the design that is least expensive to build.

IV. REFERENCES

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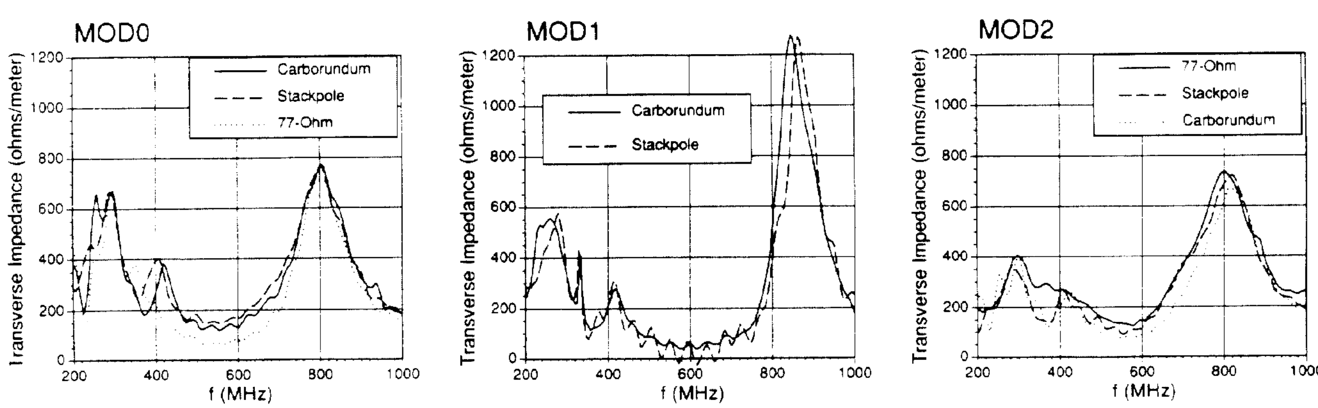

Figure 4. Effect of various compensation resistors on cavity impedances.