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CHARACTERIZATION OF A GYROTRON CAVITY AT 10 GHz

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ABSTRACT

Experiments have been conducted to characterize a gyrotron cavity designed to operate in the TE_{021} mode at 10 GHz. Small holes were introduced into the cavity to couple in and detect the probing power. Evaluation of the loaded Q factor is based on bandwidth measurements whereas standing-wave electric field profile is determined by using perturbation techniques. Good agreement between measured and predicted values of resonant frequencies and Q factors for several fundamental TE modes is found.

1. Introduction

Current gyrotron research is a very active field and is being driven by the requirements of microwave sources with capabilities up to 1 MW CW at 280 GHz for controlled thermonuclear fusion research.[1] The gyrotron is a microwave power tube that emits coherent radiation at the electron cyclotron frequency or its harmonics. It consists of electrons which follow helical paths around the lines of an externally applied magnetic field in the presence of a TE wave. The resonant wavelength is fixed by the strength of the magnetic field rather than by the scale of slow-wave structures as in most tubes. Therefore, for a given operating frequency, gyrotron cavities are relatively large, allowing high power handling capability.

In this paper, we report experiments for cold testing a gyrotron-model-resonator to be used in a 35 GHz, 100 kW gyrotron currently under construction at INPE.[2] The model resonator has been manufactured by electroforming methods [3] and, since Ka-band measurement equipments were not available at the time of experiment, the cavity was scaled up to operate at 10 GHz. In addition to examining the mode selectivity of the resonator, the experiments were focused on characterizing the nominal mode TE_{021} by measuring its resonant frequency, quality factor and axial electric field profile. The method to evaluate Q-values is based on bandwidth measurements, and standing-wave electric field profiles were determined through conventional techniques of moving a perturbing dielectric along the cavity and noting the resultant frequency shift.

2. Gyrotron Resonators

In most gyrotrons, a weakly irregular oversized waveguide operating near cutoff is used as an open resonator.[4] The cavity studied here has a cylindrical mid-section joined to two linear tapers as shown in Fig. 1.

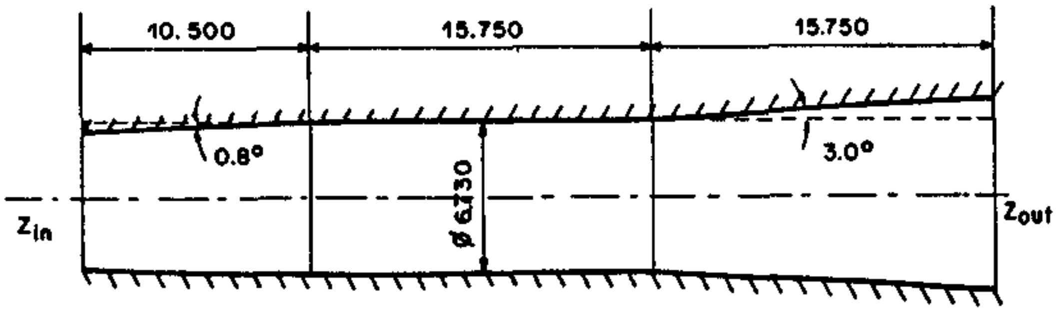

Figure 1. Cutaway view of tested resonator (dimensions in cm).

The down taper is extended far enough to ensure cutoff of the working mode whereas the up taper couples the quasi-stationary field to an outgoing travelling wave. In such a system, the electron beam interaction with RF magnetic fields is very weak and can be neglected. Therefore, throughout this paper only TE_{mnp} modes will be considered. The electric field is described by

$\vec{E} = \mathrm{Re}\,\{C_{mn}[k_{\perp,mn} J'_m(k_{\perp,mn} r)\,\tilde{\Theta} + i\,\frac{m}{r}\, J_m(k_{\perp,mn} r)\,\tilde{r}]\, V(z) \exp[i\,(wt - m\Theta)]\}$,

where J_m is a Bessel function of the first kind and $k_{\perp,mn} = X_{mn}/R_w(z)$ is the transverse wave number; X_{mn} denotes the nth non-trivial root of $J'_m(x) = 0$ and $R_w(z)$ is the waveguide radius. The normalization constant $C_{mn} = \{\sqrt{\pi\,(X_{mn}^2 - m^2)}\, J_m(X_{mn})\}^{-1}$ is introduced such that

$$2\pi \int_0^{R_w(z)} |E|^2\, r\,dr = |V(z)|^2 \tag{1}$$

where the complex function V(z) describes the longitudinal structure of a normal mode. In the single-mode approximation, i.e. for taper angles limited to 6°, V (z) satisfies the wave equation [4,5].

$$d^2V(z)/dz^2 + k_\parallel^2(z)\, V(z) = 0 \tag{2}$$

subject to appropriate radiation conditions at the cavity ends remote enough from the resonant section:

$$\left(dV/dz \mp i\, k_\parallel V\right)\Big|_{z = \{^{Zin}_{Zout}} = 0 \tag{3}$$

where $k_\parallel = (w^2/c^2 - k_{\perp,mn}^2)^{1/2}$ is the longitudinal wave number. The complex eigenfrequency is represented by $w = w_R + i w_I = w_R\,(1 + i2/Q_D)$ where Q_D is the diffraction Q factor of a cavity mode. In high power gyrotrons, the values of Q_D are typically within the interval (200-1500). These Q_D values are chosen to maximize the output power $P_{out} = P_W/(1 + Q_D/Q_\Omega)$, where P_W is the power transferred from the electron beam to the RF fields, and to minimize the wall loading $P_{\Omega_2} = (Q_D/Q_\Omega)\, P_{out}$ of the cavity where Q_Ω is the ohmic Q factor; $Q_\Omega = (1 - m^2/X_{mn}^2)\, \bar{R}_W/\delta$, where $\bar{R}_W$ denotes the mean cavity radius and δ is the skin depth.

3. Experimental Setup

Fig. 2 illustrates the experimental setup. Coupling to TE modes in the gyrotron resonator was accomplished from a standard rectangular TE_{10} waveguide injecting power through a small hole near the mid-plane of the straight section of the resonator. The hole has a diameter of about $\lambda/4$, where λ is the free-space wavelength, with the two guiding systems having some common field component over the extent of the hole. A second hole was drilled into the opposite side of the cavity to couple electromagnetic energy into the receiving waveguide connected to a network analyzer. The Q factor measured here is the total or loaded Q as determined directly from frequency readings at the half-power points on the detected spectrum. The total Q is related to the diffractive and ohmic Q by $Q_T = (1/Q_D + 1/Q_\Omega)^{-1}$.

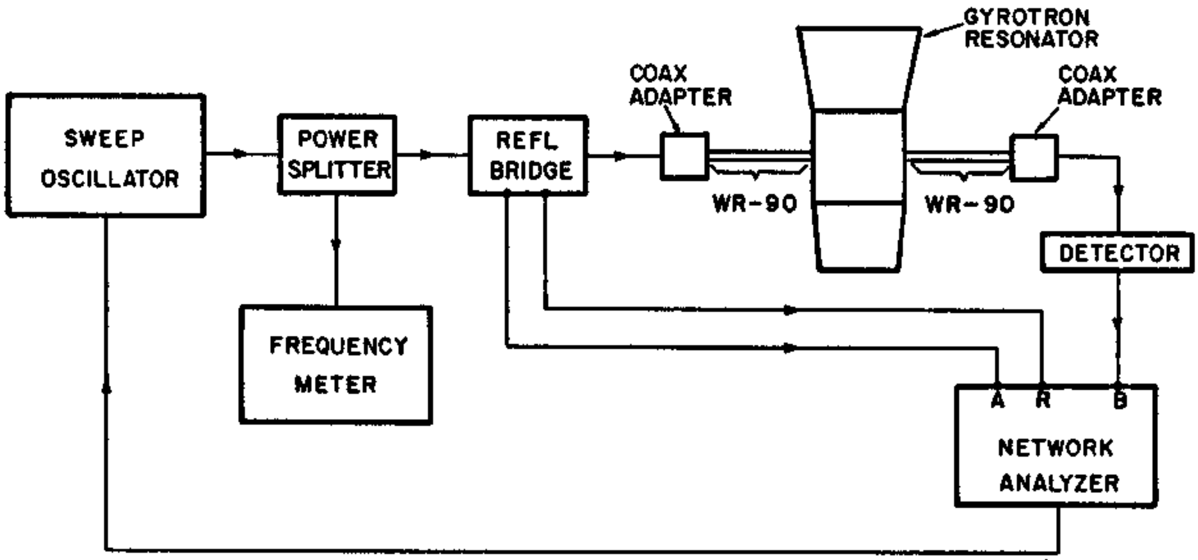

Figure 2. Schematic diagram of the experimental setup.

The variation of the electric field along the cavity axis was found by using perturbation techniques. This procedure is based on the fact that introducing a perturbing dielectric inside the cavity causes a change in the resonant frequency f_0. This change in frequency gives a measure of the electric field at the corresponding axial position, as stated by the following expression[6] : $(f-f_0)/f_0 = - \int \Delta\epsilon E^2 \, dV/U$. The numerator in the right-hand side represents integration over the volume of the perturbing object and is the change in the stored energy; $\Delta\epsilon = \epsilon_1 - \epsilon_0$, where ϵ_1 and ϵ_0 denote the permittivities for dielectric and free space, respectively. The denominator is the average energy stored in the cavity.

In the experiments, we have used a small dielectric sphere suspended in the cavity by a thin thread as well as a circular sheet of mylar attached to an insulated rod. If a sphere of radius a and permittivity ϵ_1 is introduced into the cavity at the position z, the associated frequency change is $\frac{f-f_0}{f_0} = - \frac{4\pi}{3} \frac{a^3(\epsilon_1 - \epsilon_0)|E(z)|^2}{U}$

where it is assumed that the electric field is constant in the vicinity of the perturbing sphere. In the presence of a thin disk with radius nearly equal to the waveguide radius, the resultant frequency shift is, by using eq. (2), $\frac{f-f_0}{f_0} = -\frac{d(\varepsilon_1-\varepsilon_0)\,|V(z)|^2}{U}$, where d represents the disk thickness.

4. Results

The comparison between computed and measured quantities is presented in Table 1. The ohmic Q factor was calculated by taking the value of conductivity 4.3 x 10^7 S/m for electrodeposited copper [7]. Predicted values for resonant frequency and diffraction Q factor were obtained from numerical solution of eq. (2) subject to radiation conditions (3). The agreement is fairly good where the measured frequencies are all

Table 1. Measured and predicted quantities for TE modes in the resonator tested

	CALCULATED				MEASURED	
TE MODE	Q_D	Q_Ω x 10^{-4}	Q_T	f(GHz)	Q_T	($f\pm4\times10^{-4}$)GHz
511	776	1.6	740	9.1223	637±9	9.1046
221	859	3.9	840	9.5376	800±14	9.5189
021	944	4.4	924	9.9716	931±11	9.9577
022	252	4.4	250	10.0415	-	-
023	130	4.4	129	10.1496	-	-
611	1071	1.6	1000	10.6622	958±18	10.6384
321	1240	4.0	1200	11.3872	1160±15	11.3685

slightly below the predicted values. However, other modes than the fundamental ones were not detected. As shown in Fig. 3, both exciting and detecting waveguides were soldered near the mid-section of the resonator to strongly excite the design mode TE_{021}. However, this position corresponds to the minimum of the axial profile $|V(Z)|$, and prevents p = 2 modes from being detected.

As for the TE_{023} mode, such a mode has a rather low diffraction Q factor, since Q_D scales as $\sim (L/p)^2$, where L is the effective cavity length[4]. Although the waveguides

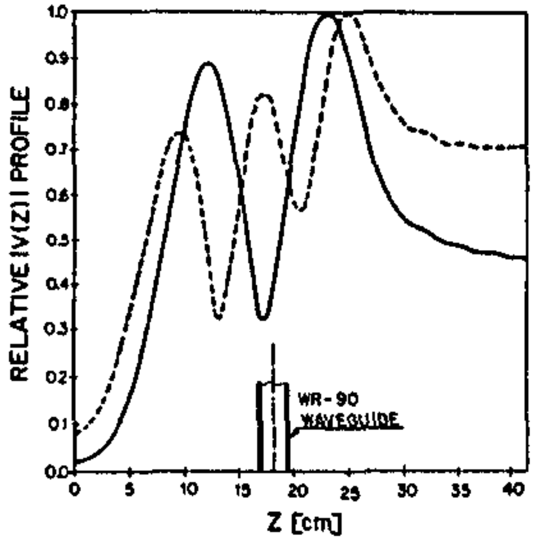

Figure 3. Calculated $|V(z)|$ profile for the TE_{022} (solid line) and TE_{023} (dashed line) modes of the gyrotron resonator (Fig. 1). Location of the waveguides is also indicated.

were located near the central maximum of the axial profile $|V(Z)|$ for the mode TE_{023} (Fig. 3), the presence of coupling holes has the effect of lowering further the diffraction Q of the mode, thus making it difficult to observe the oscillation.

To fully characterize the mode of interest, TE_{021}, its standing-wave electric field profile was determined by the perturbation method [6]. In Fig. 4(a), data obtained from a dielectric sphere are compared with theory at the points indicated. Various spheres of different diameters were tested so that a perturbation in frequency could be detected without affecting the total Q. These measurements were performed by moving a plastic sphere of 12mm diameter along the cavity axis and noting the associated frequency shift. In Fig. 4(b), similar results were achieved by plunging into the resonator a 0.025 cm thick disk of mylar with diameter nearly equal to the cavity diameter. We see that both experimental profiles appear to be more broadened than the theoretical profile due to the increasing of reflection of the cavity fields. In either case and from a qualitative stand point, the measured data assure that the electric field has one variation with respect to the axial coordinate and thus confirm p = 1 for the mode TE_{02} under observation.

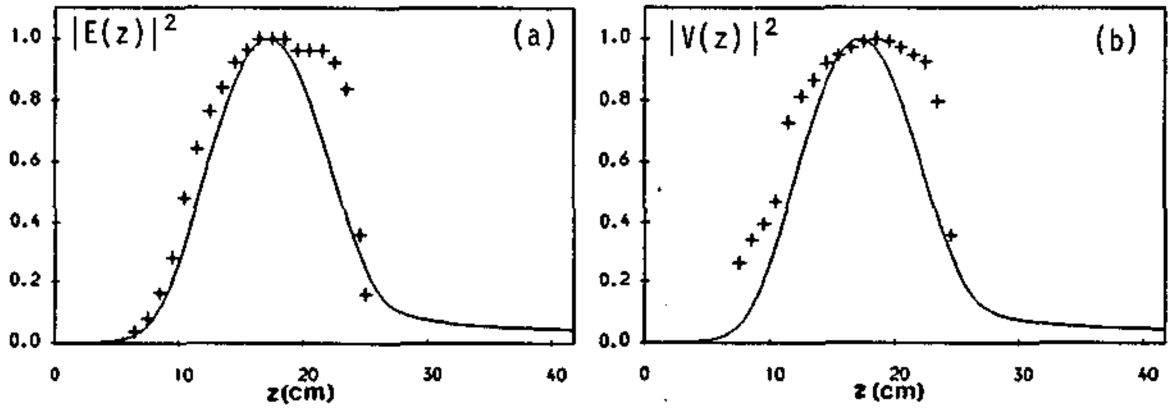

Figure 4. Predicted and measured (a) relative electric field intensity near the cavity axis and (b) $|V(z)|^2$ profile function for the TE_{021} mode.

5. Conclusion

A gyrotron cavity has been manufactured by electroforming methods and has been cold-tested. Measured data agree well with predicted values of resonant frequency and loaded Q factor for several fundamental TE modes. To identify the nominal mode TE_{021}, standing-wave electric field profile measurements were carried out by using perturbation techniques. It seems likely that low Q_D-factor oscillations could not be detected due to weak coupling between the guiding systems and the mode under consideration. In any event, the experiment has confirmed the expected characteristics of the designed cavity.

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