Nondestructive Gyrotron Cold-Cavity Q Measurements

PAUL P. WOSKOBOINIKOW, MEMBER, IEEE, AND WILLIAM J. MULLIGAN

Abstract —**A novel method for cold testing a gyrotron resonator to determine its total Q is presented. Probing radiation is coupled into the resonator through its radiation pattern. A sensitive heterodyne receiver is used in the far field to detect the reradiated cavity resonances. Good agreement between measurement and calculated total Q is found for several 140-GHz gyrotron resonators in the TE_{031}, TE_{032}, TE_{231}, and TE_{611} modes.**

I. Introduction

THE DEVELOPMENT of gyrotron millimeter-wave sources is currently a very active field. The trend is toward higher power levels (over 1 MW) and higher frequencies (into the submillimeter-wavelength range). This in turn requires operation on increasingly higher order resonator modes to keep the resonator dimensions practical. For example, recent 140-GHz, >100-kW gyrotron experiments have operated in the cylindrical TE_{031} [1] and TE_{611} [2] modes. A 1-MW, 120-GHz experiment will operate in $TE_{m,p,1}$ modes with $m \gg 1$ and $p = 1$ or 2 [3]. The resonators of these and most gyrotrons are simple, straight cylinders with tapers at either end [4].

The resonator Q factor determines the gyrotron operating characteristics. High-power (>100 kW) gyrotrons, intended for electron cyclotron heating of fusion plasmas, require low Q's (<1500) to minimize resonator wall loading. Moderate-power gyrotrons (<10 kW), for applications such as plasma diagnostics [5], require high Q's (> 5000) to optimize lower power efficiency and for narrow-linewidth, stable-frequency operation. It is important to achieve the design Q of the resonator in order to realize the design performance of a gyrotron.

At the high frequencies of current interest, the tolerances for fabrication of gyrotron resonators are very small. Small cavity imperfections not apparent from visible inspection can result in resonator Q's very different from design. For example, one resonator described in this paper was designed for a diffractive Q of 7000 in the TE_{031} mode at 137 GHz, but measurements showed it to be approximately 40 000.

In this paper, we describe a simple, nondestructive method for experimentally measuring the resonator Q factor. It is based on a variation of the standard transmission resonance technique [6]. Drilling multiple holes into the cavity, as used in past application of this technique [4], is not required. Instead, we make use of the resonator radiation pattern for coupling in and detecting the probing radiation. The advantages of this method are that any resonator mode can be studied with the same experimental setup (no mode converters are required), the resonator is not damaged in any way, and any resonator configuration, including quasi-optical resonators [7], can be studied.

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The authors are with the Plasma Fusion Center, Massachusetts Institute of Technology, Cambridge, MA 02139.
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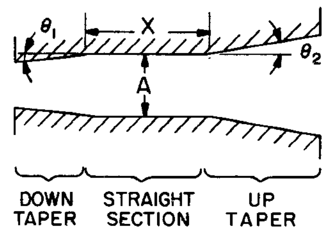

Fig. 1. Cross section of cylindrical gyrotron resonator.

II. Gyrotron Resonators

The gyrotron resonators tested here were all of the open cylindrical design originally described by Vlasov [8]. Fig. 1 illustrates this type of resonator. A straight cylindrical section with a diameter near cutoff for the desired mode has a conical down taper on one end and an up taper on the other side. The down taper is extended far enough to ensure complete cutoff of the resonator mode. The up taper couples out the millimeter-wave power. Such a resonator is simple and allows a high-power electron beam to be transmitted through it.

The resonator Q is primarily determined by the length of the straight section and the angle of the tapers. Small mechanical imperfections can significantly alter the design Q. For example, a slight barrel shape to the straight section or steps at the taper transitions can increase the Q, while a slightly up-tapered straight section would lower the Q. It is also important to note that for modes well below cutoff this resonator is just an overmoded irregular waveguide readily passing a millimeter-wave beam.

The Q measurement technique described here is not limited to this gyrotron resonator design. This type of resonator was studied because currently it is the most commonly used in gyrotrons and several such resonators were available for testing. However, this technique could be applied to more complex cavities which have a stepped straight section, slots, or coaxial conductor since this technique is independent of the internal structure of the resonator. Quasi-optical Fabry–Perot-type resonators being

TABLE I
DIMENSIONS OF TESTED GYROTRON RESONATORS

CAVITY (Design Q_D)	A (inches)	X (inches)	θ_1	θ_2
ELECTROFORMED (1500)	0.274	0.505	0.5°	4°
ELECTROFORMED (400), TE_{611}	0.197	0.252	0.5°	4°
ELECTROFORMED (7000)	0.279	1.130	1°	2°
MACHINED (9000)	0.279	1.245	1°	2°
MACHINED (6000)	0.279	1.063	1°	2°
ELECTROFORMED SILVER PLATED (7000)	0.279	1.130	1°	2°

developed for high-frequency operation could also be studied.

Six different gyrotron resonators with design diffractive Q's ranging from 400 to 9000 were tested. Some of these resonators were assembled from three machined copper parts (down taper, straight section, and up taper) and others were electroformed as a single piece. Table I lists the parameters identified in Fig. 1 of the resonators tested. All except one were designed for operation in the TE_{031} mode at about 140 GHz, the exception being the TE_{611} whispering-gallery-mode resonator.

III. Q FACTOR

The resonator Q factor measured here is the total or loaded Q as determined by the ratio of the measured resonance linewidth at half maximum to the absolute resonance frequency. It is related to the diffractive and ohmic Q by

$$Q_T = \left(Q_D^{-1} + Q_\Omega^{-1}\right)^{-1}. \tag{1}$$

The diffractive Q, Q_D, describes the balance between the energy stored in the cavity, E_s, and the output coupled power P. It can be defined as $Q_D = \omega E_s / P_o$. Previous analyses [8], [9] of cylindrical gyrotron cavities have shown that

$$Q_D = \frac{4\pi}{(1 - R_1 R_2)} \left[\frac{L}{\lambda}\right]^2 \tag{2}$$

where R_1 and R_2 are the reflectivities at the ends of the cavity (the down taper end reflectivity R_1 is generally equal to one) and L is the axial length of the stored field. A computer code [10] which simulates the field in the cavity was used to calculate the diffractive Q's of the resonators tested.

The ohmic Q, Q_Ω, describes the balance between the energy stored in the cavity and the power coupled to the resonator walls. It is given by

$$Q_\Omega = \frac{R_0}{\delta}\left(1 - \frac{m^2}{\nu_{mp}^2}\right) \tag{3}$$

where R_0 is the cavity radius, δ is the skin depth, ν_{mp} is the pth zero of the J_m' Bessel function, and m and p are the mode indices as previously defined.

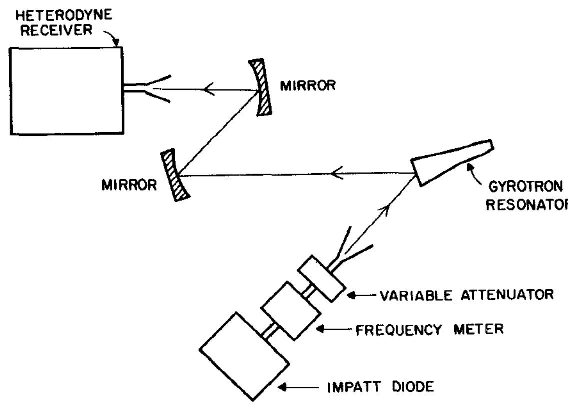

Fig. 2. Experimental setup.

IV. EXPERIMENTAL SETUP

The experimental setup is illustrated in Fig. 2. The source of probing radiation was a 10-mW, 135–144-GHz tunable IMPATT diode. The radiation, which was reflected or reradiated by the gyrotron resonator under test, was detected with a heterodyne receiver. For most of the measurements, this receiver consisted of: a 46 ± 0.25-GHz Gunn diode and Millitech frequency tripler as the local oscillator (LO), a Hughes single-ended mixer, a 3-dB directional coupler as the diplexer, and 5–1500-MHz intermediate-frequency (IF) amplifiers with a total gain of 60 dB. Higher frequency IF amplifiers were also used to increase the frequency range covered. Standard Hughes 24-dB gain horns were used both at the receiver and the IMPATT diode. The receiver noise temperature was approximately 10 000-K double sideband.

The gyrotron resonator under test was placed in the receiver field of view, which was approximately collimated with some focusing mirrors. The resonator was angled so that a peak or null of the resonator mode far-field pattern was directed toward the receiver. The IMPATT diode beam was coupled into the cavity from a direction opposite the receiver with respect to the resonator axis. The precise alignment of the resonator and IMPATT diode was adjusted experimentally for a good signal.

The key to the success of this measurement technique is the use of a heterodyne receiver for detection. Because of its sensitivity, it could be placed very far in the far field, up to 2 m. This allowed for good resolution of a feature in the far-field pattern and eliminated any interaction between the resonator under test and the receiver. The output diameter of the resonators tested was either 1.27 or 2.20 cm, so the far field ($R > D^2/\lambda$) was greater than 7.5 or 22 cm away, respectively. However, best cavity resonances were observed with the IMPATT diode horn very close to the test cavity, within 10 cm. About 20 dB of attenuation was typically used at the IMPATT diode because signal levels were more than adequate.

V. MEASUREMENTS

The measurements were made by rapidly sweeping the IMPATT diode frequency and displaying the detected spectrum on an oscilloscope. For the correct resonator

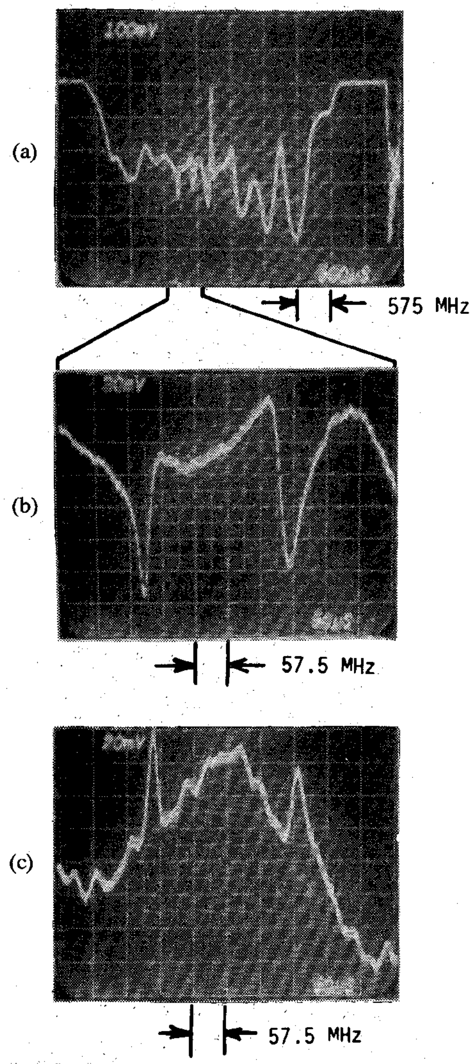

Fig. 3. Results for a machined 137-GHz, TE_{03} resonator with $Q_D = 9000$. Oscilloscope displays are shown of the receiver signal (going negative) with IMPATT diode frequency swept at 1.15 MHz/μs. (a) Full double-sideband output from receiver. TE_{031} and TE_{032} cavity resonances evident in lower sideband. (b) Cavity resonances on expanded scales appear as emission peaks. (c) For different resonator orientation, cavity resonances appear as absorptions.

orientation, a small fraction of the IMPATT power was coupled to the resonator mode and the cavity resonances appeared in the displayed spectrum. Typical receiver signals are illustrated in Fig. 3, which shows the results for a machined 137-GHz, TE_{03} resonator with a design $Q_D = 9000$.

The full double-sideband output from the receiver is shown in Fig. 3(a). Signal levels are negative. The sharp null near the middle of the trace corresponds to receiver IF frequencies between ± 5 MHz, which are not amplified. This null serves as a frequency reference marker, corresponding to an LO frequency of 137.5 GHz in this case. The frequency sweep rate was 1.15 MHz/μs from low to high frequencies. The detected spectrum is modulated by a standing wave, which is particularly evident in the upper sideband. Cavity resonances can be observed in the lower sideband superimposed on the standing-wave pattern.

The output from the IMPATT diode was not flat across the frequency range studied. When the receiver viewed the diode directly or by way of a mirror in place of the gyrotron resonator, the signal was generally increasing from low to high frequency, as roughly the average level in Fig. 3(a) would indicate. Furthermore, there was some structure as a function of frequency, which causes the standing pattern in Fig. 3(a) to look uneven. However, the standing pattern is very pronounced over the normal unleveled IMPATT signal when the gyrotron resonator is introduced into the setup.

In Fig. 3(b), the resonances are shown on expanded scales. These peaks are negative going, which could be interpreted as emission peaks. Different resonator orientations are also possible where these peaks appear as absorptions, as shown in Fig. 3(c). The background standing-wave pattern also varies with resonator orientation. Best results are obtained if the cavity is oriented so that a resonance occurs on a peak or minimum of the standing-wave pattern. In this way, the half maximum width of the resonance can be more accurately determined for the Q measurement. A by-product of this measurement is an accurate determination of the cavity resonant frequencies.

The resonances in Fig. 3 were identified as the TE_{031} and TE_{032} modes. Their frequency separation of 250 MHz agrees with computer calculations [5], [10], and the width of the TE_{032} resonance is larger, as expected, for the lower Q mode. For higher order axial modes, Q scales inversely as the square of the axial mode number. The results for this resonator and the others tested are listed in Table I.

In order to make a comparison of the measured total Q with the design diffractive Q, the ohmic Q was calculated by assuming the standard published value for copper conductivity of 59×10^6 mho/m to calculate the skin depth. Measurements of electrodeposited copper conductivity at millimeter-wave frequencies have shown this to be a good assumption [12].

Good agreement between measured and calculated total Q was obtained for the first four resonators listed in Table II. The electroformed 1500- and 400-design Q_D cavities and the machined 6000-design Q_D cavity are the same ones used in gyrotrons previously reported [11], [2], [5]. The machined gyrotron resonators, assembled from parts, are susceptible to higher Q values than design if the resonator parts are not precisely mated or aligned. This may be the reason for the high value measured for the 6000-design Q_D cavity.

The most interesting difference between measurement and calculated total Q was for the last cavity listed in Table I. This was an electroformed resonator which was silver plated in an attempt to improve ohmic Q slightly. Use of this resonator in a gyrotron resulted in poor performance. Competition between the TE_{031}, TE_{032}, and TE_{033} modes was observed, with the best output efficiency achieved in the TE_{032} mode. Cold testing explained these results. The measured total Q for the TE_{032} mode corresponded to a diffractive Q of 10 000. The TE_{031} mode was not observed in cold testing, but scaling the diffractive Q

TABLE II
COMPARISON OF MEASURED AND CALCULATED GYROTRON RESONATOR TOTAL Q FACTOR

CAVITY (DESIGN Q_D)	MODE	FREQUENCY (GHz)	Q_T MEASURED	Q_T CALCULATED*
ELECTROFORMED (1500)	TE_{031}	139.75	1520 ± 200	1400
	TE_{231}	136.65	1600 ± 200	1400
ELECTROFORMED (400)	TE_{611}	143.06	550 ± 100	370
ELECTROFORMED (7000)	TE_{031}	136.70	5700 ± 400	5200
	TE_{032}	136.93	2000 ± 200	1600
MACHINED (9000)	TE_{031}	136.95	7000 ± 600	6200
	TE_{032}	137.20	3100 ± 300	2000
MACHINED (6000)	TE_{031}	137.18	6800 ± 600	4600
	TE_{032}	137.48	2400 ± 300	1400
ELECTROFORMED SILVER PLATED (7000)	TE_{031}	136.90	13,400**	5200
	TE_{032}	137.27	6,700 ± 600	1600

*Using Q_Ω with copper conductivity assumed to be 59×10^{16} mho/m.
**Determined from TE_{032} measurement.

as the inverse square of the axial mode number implies a value of 40 000. Subsequent inspection of the resonator with a reaming tool revealed a slight barrel shape to the straight section. This example supports the validity of this Q measurement technique.

The main source of error for these measurements is the standing-wave background on which the resonances are superimposed. Using eccosorb [13] wherever possible around the outside of the test cavity had little effect. Apparently, this background is due to a coherent interference between components of the probing radiation which are reflected from the front and back ends of the resonator. Most of the IMPATT diode radiation is not coupled to the resonator mode and is transmitted through the cavity. For this radiation, the gyrotron resonator acts as a short length of overmoded waveguide. At the ends of such a waveguide there is some reflection.This interpretation is supported by the observation that the cavity resonances appear as absorptions on the standing-wave peaks and emissions at the standing-wave minimums when a null in the far-field pattern is aligned toward the receiver. For this orientation, the cavity resonance interferes with the reflection from the back end of the resonator, which tends to null out the standing wave.

Another observation which supports this interpretation occurs when the orientation of the IMPATT diode in the near field is varied. The frequency of the displayed standing wave varies in proportion to the angle of incidence of the probe radiation with respect to the resonator axis. Doubling the incidence angle halves the number of beats in the output display. This would be expected if the path difference between the two interfering components increased with angle.

It seems unlikely that this standing-wave background can be eliminated without affecting the resonator under test. Nevertheless, this technique for Q measurements should be accurate enough for most purposes.

VI. CONCLUSIONS

The gyrotron resonator cold-cavity Q measurement technique described here is simple to implement, does not require damaging the cavity, and is not mode-specific. Making use of the resonator radiation pattern for coupling in and detecting the probing radiation makes this technique very general, applicable to any gyrotron resonator. In particular, it will be useful for future high-power, high-frequency gyrotrons, which will operate on higher order resonator modes for which reliable Q measurement techniques have not yet been demonstrated.

Measurements presented in this paper agreed well with most design values of resonators used in successful gyrotron operation. In one case, poor gyrotron performance was explained by a measured Q value very different from design. The checking of resonator Q is necessary to avoid wasting time and effort in assembling gyrotrons which will not meet performance goals. Such a method will also be valuable for developing novel resonators which minimize mode competition. This Q measurement technique should become very useful.

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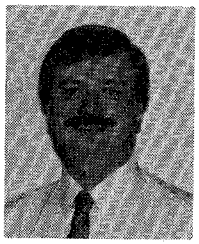
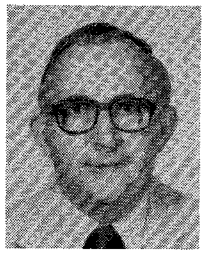


Paul P. Woskoboinikow (S'74–M'76) was born in Watkins Glenn, NY, on April 23, 1950. He received the B.S. degree in physics in 1972 and the M.S. and Ph.D. degrees in electrical engineering in 1974 and 1976, respectively, all from Rensselaer Polytechnic Institute, Troy, NY.

From 1976 to 1979, he was a staff scientist at the Francis Bitter National Magnet Laboratory at the Massachusetts Institute of Technology, where he worked on the development of high-power, laser-pumped far-infrared molecular lasers. Since 1980, he has been with the Plasma Fusion Center at the Massachusetts Institute of Technology. He is currently project leader for the development of millimeter- and submillimeter-wave diagnostics for fusion plasmas. He has worked with both the Alcator tokamak and Tara tandem mirror groups. His current research interests include gyrotrons, mode converters, millimeter–submillimeter-wave receivers, and fusion plasma diagnostics.

Dr. Woskoboinikow is a member of the American Physical Society.



William J. Mulligan was born in County Mayo, Ireland, on February 7, 1925. He received the A.E. degree in electronics and the B.B.A. degree in engineering and management from Northeastern University, Boston, MA, in 1957 and 1959, respectively.

From 1956 to 1976, he worked at the Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, where he designed and fabricated electronic and high-voltage equipment related to plasma physics and lasers. In 1976, he joined the Plasma Fusion Center, Massachusetts Institute of Technology, Cambridge, where he is currently a Technical Staff Member involved in submillimeter laser and gyrotron research and development.