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Non-Destructive Gyrotron Cold
Cavity Q Measurements

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ABSTRACT

A novel method for cold testing a gyrotron resonator for total Q is presented. Probing radiation is coupled into and out of the resonator through its radiation pattern. A sensitive heterodyne receiver is used in the far field to detect the cavity resonances. Good agreement between measurement and calculated total Q is found for several 140 GHz gyrotron resonators in the TE₀₃₁, TE₀₃₂, TE₂₃₁, and TE₆₁₁ 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 7,000 in the TE_{031} mode at 137 GHz, but measurements showed it to be approximately 40,000.

In this paper we describe a simple, non-destructive 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: any resonator mode can be studied with the same experimental set up (no mode converters are required); the resonator is not damaged in any way; and it is not dependent on resonator design, applicable even to quasi-optical gyrotrons[7].

II. Q FACTOR

The resonator Q factor measured here is the total or loaded Q. It is related to the diffractive and ohmic Q by

$$Q_T = (Q_D^{-1} + Q_\Omega^{-1})^{-1} \quad (1)$$

The tested resonators were designed for diffractive Q's as determined by a computer code described in [8]. The ohmic Q is given by the equation

$$Q_\Omega = \frac{R_O}{\delta} \left(1 - \frac{m^2}{v_{mp}^2} \right) \quad (2)$$

where R_O is the cavity radius, δ is the skin depth, v_{mp} is the pth zero of the J'_m Bessel function, and m and p are the mode indices as previously defined. For comparison with the measurements the published value for copper conductivity of 59 mhos/m was used for calculating ohmic Q.

III. EXPERIMENTAL SET UP

The experimental set up is illustrated in Fig. 1. The source of probing radiation was a 10mW, 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 $46 \pm .25$ GHz Gunn diode and Millitech frequency tripler as the local oscillator (LO), a Hughes single ended mixer, a 3dB directional coupler as the diplexer, and 5-1500 MHz intermediate frequency (IF) amplifiers with a total gain of 60dB. Higher frequency IF amplifiers were also used to increase the frequency range covered. Standard Hughes 24dB gain horns were used both at the receiver and Impatt diode. The receiver noise temperature was approximately 10,000K double side band.

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 2m. 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 2.54cm so the far field ($R > D^2/\lambda$) was greater than 7.5 or 30cm away, respectively. However, best cavity resonances were observed with the Impatt diode horn very close to the test cavity, within 10cm. About 20dB of attenuation was typically used at the Impatt diode because signal levels were more than adequate.

IV. MEASUREMENTS

The measurements were made by rapidly sweeping the Impatt diode frequency and displaying the detected spectrum on an oscilloscope. Six different gyrotron resonators were tested with design diffractive Q's ranging from 400 to 9000. Some of these resonators were assembled from three machined copper parts (down taper, straight section, and up taper) and the others were electroformed as a single piece. Typical receiver signals are illustrated in Fig. 2 which shows the results for a machined 137 GHz, TE₀₃ resonator with a design Q_D = 9000.

The full double sideband output from the receiver is shown in Fig. 2a. 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 L0 frequency of 137.5 GHz in this case. The frequency sweep rate was 1.15 MHz/ μ s from low to high frequencies. The detected spectrum is modulated by a standing wave which originates in the resonator under test. Cavity resonances can be observed in the lower sideband superimposed on the standing wave pattern.

In Fig. 2b these resonances are shown on expanded scales. The 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. 2c. 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 resonate frequencies.

The resonances in Fig. 2 were identified as the TE_{031} and TE_{032} modes. Their frequency separation of 250 MHz agrees with computer calculations[5,8] and the width of the TE_{032} resonance is larger as expected for the lower Q mode. The results for this resonator and the others tested are listed in Table I.

Good agreement between measured and calculated total Q was obtained for the first four resonators listed in Table I. 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[9,2,5]. 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 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 as the inverse square of the axial mode number implies a value of 40,000. Subsequent inspection of the resonator straight section with a reaming tool revealed small constrictions ($<25 \mu\text{m}$) at the input and output. 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[10] 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 inside the front and back ends of the resonator. 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 blocks the reflection from the back end of the resonator. Another observation which supports this interpretation is that the frequency separation between the standing wave peaks decreases in proportion to increasing angle of incidence of the probe radiation with respect to the resonator axis. This would be expected if the path difference between the two interfering components increases with angle.

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

V. 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 wasted time and effort in assembling gyrotrons which will not meet performance goals. Such a method will also be valuable for developing novel new resonators which minimize mode competition. This Q measurement technique should become very useful.

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FIGURE CAPTIONS

1. Experimental set up.
2. Results for a machined 137 GHz, TE_{03} resonator with $Q_D = 9,000$.
Oscilloscope displays are shown of the receiver signal (going negative) with Impatt diode frequency swept at 1.15 MHz/ μ s. (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.

TABLE I

COMPARISON OF MEASURED AND CALCULATED
GYROTRON RESONATOR TOTAL Q FACTOR

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

* Using Q_Ω with copper conductivity assumed to be 59 mhos/m

**Determined from TE₀₃₂ measurement

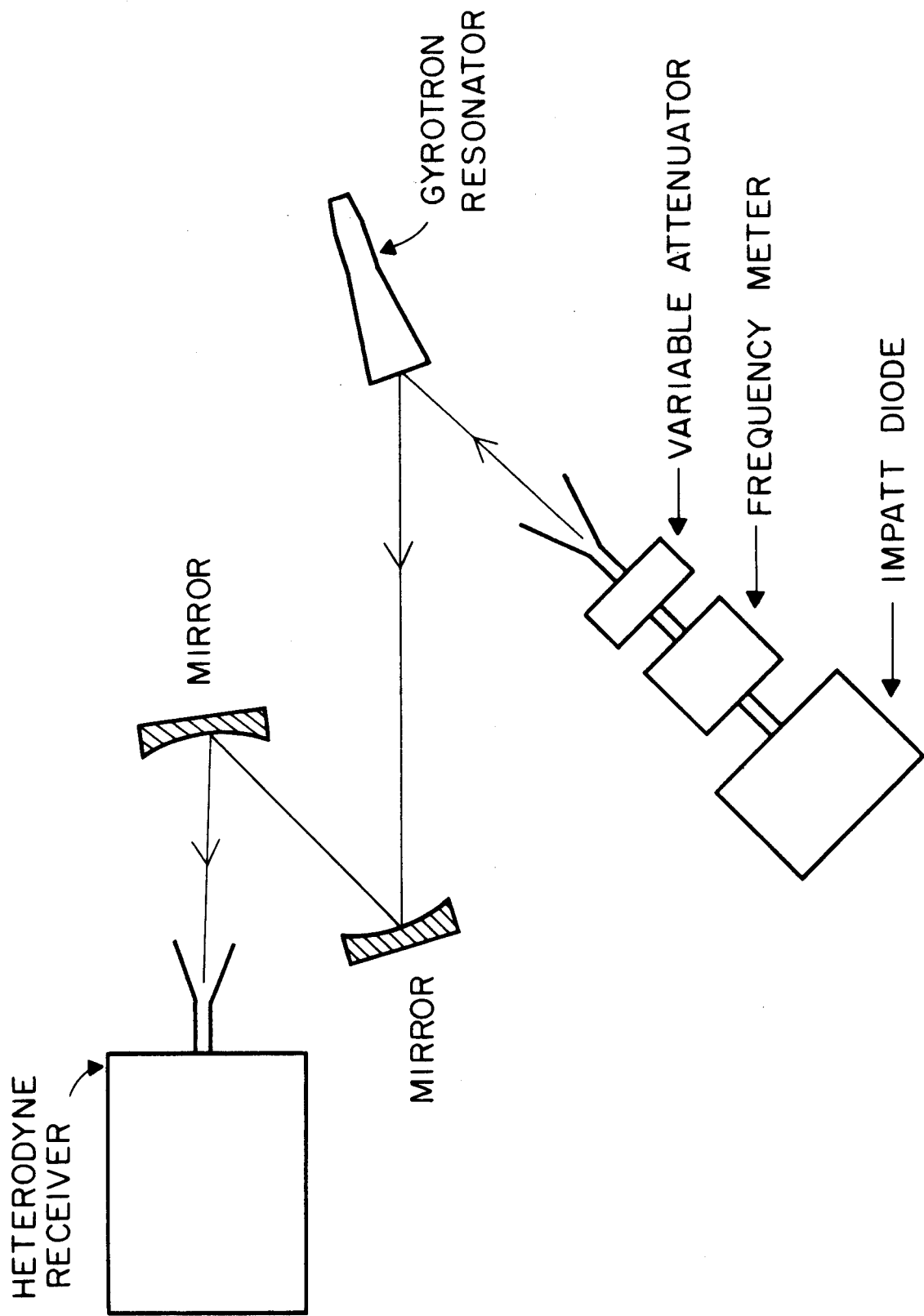


Fig. 1

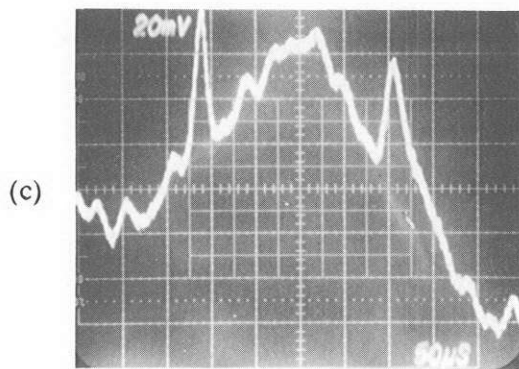
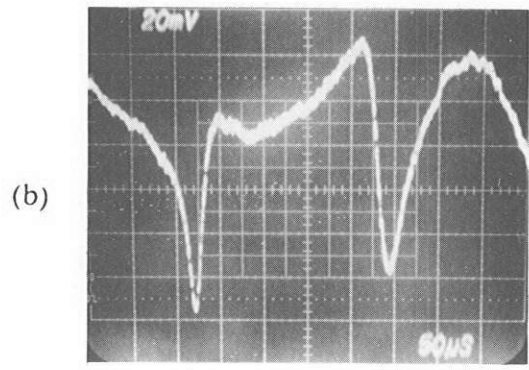
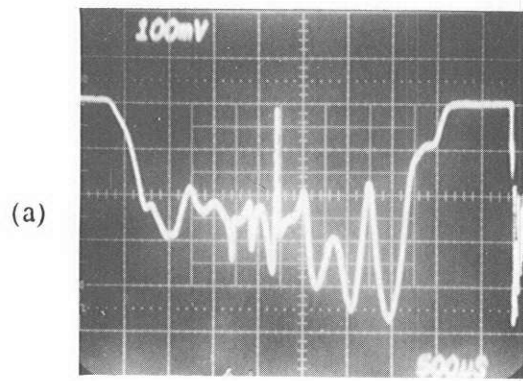


Fig. 2.