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Ohmic Quality Factor and Efficiency Estimation for a Gyrotron Cavity

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***Abstract*—**Operating a device at high power and high frequency is a major problem because wall losses greatly reduce the efficiency of the device. In the present communication, authors analytically analyzed the dependence of ohmic/RF efficiency, the fraction of output power with respect to the total power generated, of gyrotron cavity structure on the conductivity of copper for the second harmonic $TE_{0,6}$ mode. This study shows a rapid fall in the RF efficiency as the quality (conductivity) of copper degrades. Starting with an RF efficiency near 40% at the conductivity of ideal copper (5.8×10^7 S/m), the RF efficiency decreases (upto 8%) as the copper quality degrades. Assuming conductivity half that of ideal copper the RF efficiency as a function of diffractive quality factor, Q_{diff}, has been studied. Here the RF efficiency decreases rapidly with increasing diffractive Q. Ohmic wall losses as a function of frequency for 460 GHz gyrotron cavity excited in $TE_{0,6}$ mode has also been analyzed. For 460 GHz cavity, the extracted power is reduced to 32% of the generated power due to ohmic losses in the walls of the cavity.

***Keywords*—**Diffractive quality factor, Gyrotron, Ohmic wall losses, Open cavity resonator, RF Efficiency.

I. INTRODUCTION

THE development of high power microwave sources has opened up a number of possible applications. There are two ways in which the new generation of sources enhances capability, first they extend to new regimes of peak power (for example, relativistic backward wave oscillators: >0.5GW), and second, they extend high power capability to millimeter and sub-millimeter wavelength regimes. Particularly in the mm-wave band, the recent development of gyro-klystrons, gyro-traveling-wave amplifiers, gyrotwystrons and gyrotron oscillators can deliver average radiation power by several orders of magnitude [1-14].

The possible applications of gyrotrons span a wide range of technologies. The plasma physics community has already taken advantage of the recent developments of gyrotrons in the areas of RF plasma production, heating, non-inductive current drive, plasma stabilization and active plasma diagnostics for magnetic confinement, thermonuclear fusion research, such as lower hybrid current drive (LHCD) (8GHz), electron cyclotron resonance heating (ECRH) (28-170 GHz), electron cyclotron current drive (ECCD), collective Thomson scattering (CTS) and heat-wave propagation experiments [30]. Other important applications are: electron cyclotron resonance (ECR) discharges for the generation of multi-charged ions and soft X-rays, industrial material processing, plasma chemistry, high frequency-broadband electron paramagnetic resonance (EPR) spectroscopy, and high-resolution radar [15-20].

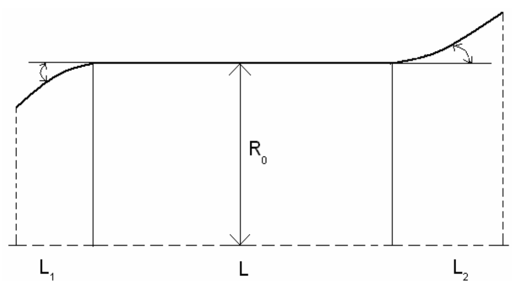

Fig. 1 Gyrotron cavity resonator

The gyrotron oscillator is a high power high frequency coherent radiation source in which the magnetron injection gun produces an annular electron beam with the desired beam parameters, the beam is transported to the interaction region where the interaction cavity converts a fraction of beam power to the RF power and the spent beam will be collected at the output collector [21-25]. The interaction region is usually a three section smooth walled cylindrical open resonator cavity (Fig. 1). The input taper is a cut-off section which prevents backward waves towards the gun. Interaction takes place between RF wave and electron beam mainly in the uniform middle section where RF fields reach peak values. The up-taper connects the cavity with the output waveguide and the launcher. Cavity design becomes more stringent if one wishes to operate the device at elevated frequencies and higher power levels from long-pulse to CW operation. The problem of wall losses is important for long pulse to CW operation of high power gyrotrons [26-29]. Wall losses are related to ohmic quality factor as $Q_{ohm}P = \omega W$; where Q_{ohm} is ohmic quality factor, P is loss in the cavity, ω is angular frequency of operation and W is the total energy stored in the cavity resonator. Knowledge of ohmic quality factor is useful for efficiency estimations [30-31].

The organization of the paper is as follows. In Section II, cavity resonator analysis for diffractive quality factor and

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efficiency have been dealt with. Finally, the results and discussion have been given in Section III.

II. Cavity Resonator Analysis

A. Diffractive Quality Factor

The type of cavity considered is shown in Fig. 1. It is a three-section cavity with a down-taper cutoff section, a uniform mid-section where the interaction between the electromagnetic field and electron beam occurs, and an up-taper section which joins the cavity to the output waveguide and the launcher of the quasi-optical coupler. The motivation for increasing the cavity quality factor is the fact that as the transverse cavity size is increased to handle high power, the coupling efficiency of the beam and radiation decreases. Thus, to access the high efficiency operation point it is necessary to raise the cavity quality factor. The time τ for energy to travel out of the cavity determines diffractive quality factor and is related as

$$Q_{d,\min} = \omega\tau = \omega\frac{L}{v_g} = \omega\frac{L}{c^2/v_p} = \frac{\omega L}{c^2}\frac{\omega}{\beta} = 4\pi\frac{L^2}{\lambda^2}$$

(Putting, $\beta L = \pi$)

where Q_d, L, v_g, v_p, c, β, and λ are diffractive quality factor, effective length of the cavity, group velocity, phase velocity, velocity of light, axial propagation constant and wavelength at operating frequency, respectively.

The actual quality factor is somewhat different due to the reflection ρ at the end of the cavity [30]. Now quality factor becomes

$$Q = \omega\frac{W}{P} = \frac{Q_{d,mim}}{\tau_d}\frac{W}{P} = \frac{Q_{d,\min}}{P\tau_d/W}$$

Since,

$$\frac{P\tau_d}{W} = \frac{\text{Energy lost during the time energy travels out of cavity}}{\text{Energy stored in the cavity}} = \frac{1}{1-\rho}$$

Thus we have,

$$Q = \frac{Q_{d,\min}}{1-\rho} = 4\pi\frac{L^2}{\lambda^2}\left(\frac{1}{1-\rho}\right) \quad (1)$$

In a long wavelength gyrotron, the total Q is approximately equivalent to the diffractive Q_d, resulting in negligible ohmic losses. However, at short wavelengths, the ohmic losses can severely reduce the output power of a gyrotron [27].

B. Efficiency

The ratio of output RF power to the input beam power gives total efficiency,

$$\eta_{out} = \frac{P_{out}}{P_{in}} = \eta_{el}\times\eta_Q \quad (2)$$

The electronic efficiency, $\eta_{el,}$ accounts for the fraction of beam power in the perpendicular direction and η_Q is the reduction due to ohmic losses. The electronic efficiency is given by

$$\eta_{el} = \frac{\beta_0^2}{2\left(1-\gamma_0^{-1}\right)}\eta_\perp \quad (3)$$

where γ_0 is relativistic mass factor and $\eta_\perp$ is efficiency due to beam power in perpendicular direction.

And η_Q is the reduction in efficiency due to ohmic losses given by

$$\eta_Q = 1-\frac{Q}{Q_{ohm}} \quad (4)$$

The total Q of a resonant cavity is given by

$$\frac{1}{Q} = \frac{1}{Q_{diff}} + \frac{1}{Q_{ohm}} \quad (5)$$

The ohmic quality factor of a cavity excited in $TE_{m,p}$ mode is given by

$$Q_{ohm} = \frac{R_0}{\delta}\left(1-\frac{m^2}{v_{mp}^2}\right) \quad (6)$$

where $\delta = (\pi f\mu_0\sigma)^{-1/2}$ is the skin depth at frequency f for the cavity having radius R_0, conductivity σ; μ_0 is absolute permeability, and v_{mp} is the eigenvalue where m and p denote azimuthal and radial index of the $TE_{m,p}$ mode.

The RF efficiency is expressed as

$$\eta_{RF} = \frac{Q_{ohm}}{Q_{diff}+Q_{ohm}} \quad (7)$$

III. Results And Discussion

The main contribution to the value of ohmic losses is the method, material and the process of fabrication of cavity. Starting with RF efficiency near 40% at the conductivity of ideal copper 5.8 x 10^7S/m, the RF efficiency rapidly decreases as the quality of copper degrades (Fig. 2). Assuming conductivity half that of ideal copper the RF efficiency as a function of diffractive quality factor, Q_{diff}, shows a rapid fall in RF efficiency with increasing diffractive quality factor (Fig. 3).

It is clear from (1) that quality factor Q is proportional to the square of the frequency,

$$Q = 4\pi\frac{L^2}{\lambda^2}\left(\frac{1}{1-\rho}\right) \propto f^2$$

and the ohmic quality factor is proportional to the square root of the frequency, as per (6),

$$Q_{ohm} = \frac{r_0}{\delta}\left(1-\frac{m^2}{v_{mp}^2}\right) \propto \sqrt{f}\ .$$

That is why ohmic loss increases rapidly with frequency and imposes a limit for output power at high frequencies. If cavity size is increased, the ohmic losses can be reduced. But this makes mode competition more severe. Thus cavity design is a compromise between several factors.

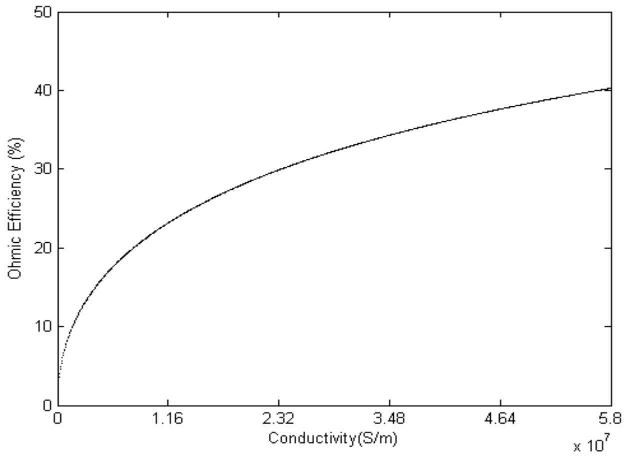

Fig. 2 Ohmic efficiency as a function of conductivity of cavity wall

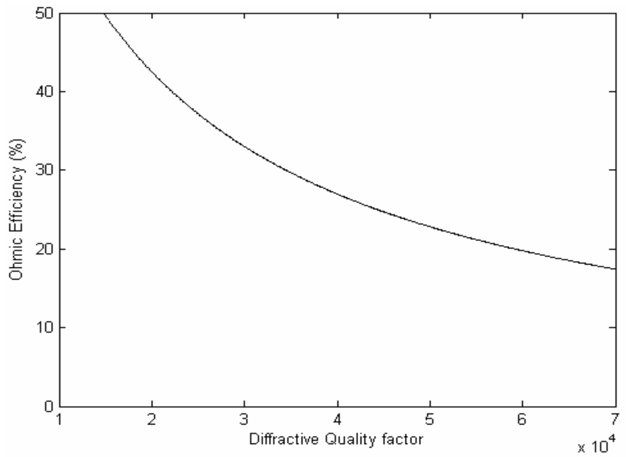

Fig. 3 Ohmic efficiency as a function of diffractive Q of cavity

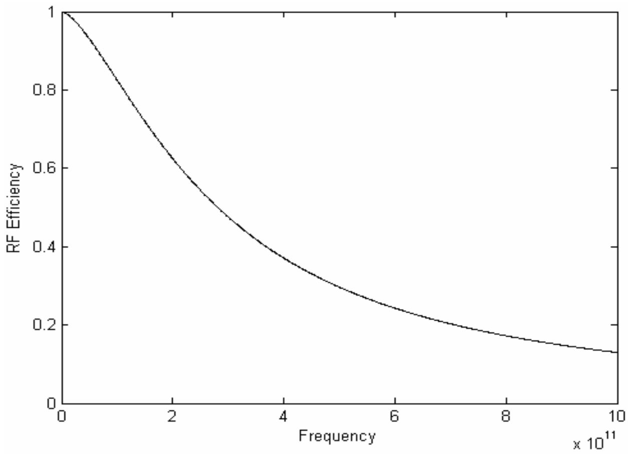

Fig. 4 RF efficiency as a function of frequency (Hz) for $TE_{0,6}$ mode

Fig. 4 shows ohmic losses as a function of frequency for the 460 GHz cavity operating in $TE_{0,6}$ mode. The extracted power is reduced to 32% of the generated power due to ohmic losses in the walls of the cavity at the operating frequency. It indicates that a significant portion of the power generated in the cavity is not extracted and is instead deposited in the cavity walls in the form of ohmic heating.

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