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Ohmic Effects in Quasioptical Resonators

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Several properties of the Fabry-Perot-type open resonator used in the quasioptical gyrotron (QOG) and the quasioptical induced resonance electron cyclotron (IREC) maser are derived. The electric fields of the normal modes are given for the general case of the resonator axis tilted with respect to the direction perpendicular to the electron beam axis. The ohmic quality factor and the power dissipated in the mirrors is derived, as is the energy stored in the resonator. The time dependence of the mirror heating, useful for pulsed experiments, is also derived. The formulae are applied to an example of current relevance, the IREC maser resonator.

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OHMIC EFFECTS IN QUASIOPTICAL RESONATORS

I. Introduction

The quasioptical gyrotron (QOG) has been under investigation at NRL for several years as a potential source of high-power radiation at frequencies above 100 GHz for electron cyclotron resonance heating (ECRH) of fusion plasmas.[1, 2, 3, 4] An integral part of the QOG is the resonator, which traps some of the radiation emitted by the electron beam, allowing the radio frequency (rf) fields to grow to the large values necessary for efficient extraction of energy from the beam. The QOG resonator suffers losses due to diffraction of the radiation around the outer edge of the resonator mirrors as well as the finite conductivity of the mirror surfaces. Clearly, it is imperative to understand each of these loss mechanisms in order to understand the operation of the QOG experiments. This note addresses the ohmic losses in the resonator, deriving expressions for the electric field in the resonator, the ohmic quality factor (Q_Ω), the ohmic heating density (ρ_Ω), the total ohmic power (P_Ω) dissipated in the resonator mirrors, and the temperature rise of the mirrors. The derived formulae are then applied to the current design of the cavity to be utilized in the NRL induced resonance electron cyclotron (IREC) maser experiment.

II. Cavity Fields

The resonator considered here consists of the Fabry-Perot-type open resonator shown in Fig. 1. The spherical cavity mirrors form an azimuthally symmetric resonator about the cavity (y') axis, which is offset by an angle θ from the y-axis as shown in Fig. 2. The angle θ is used in the QOG literature,[5] however, in the IREC maser literature[6] the angle ψ between the resonator (y') and the electron beam (z) axes is typically used. The mode structure and stability of this type of resonator is discussed by Yariv[7] who finds that the electric field of the transverse electric and magnetic ($\mathrm{TEM}_{m,n,l}$) modes of the travelling

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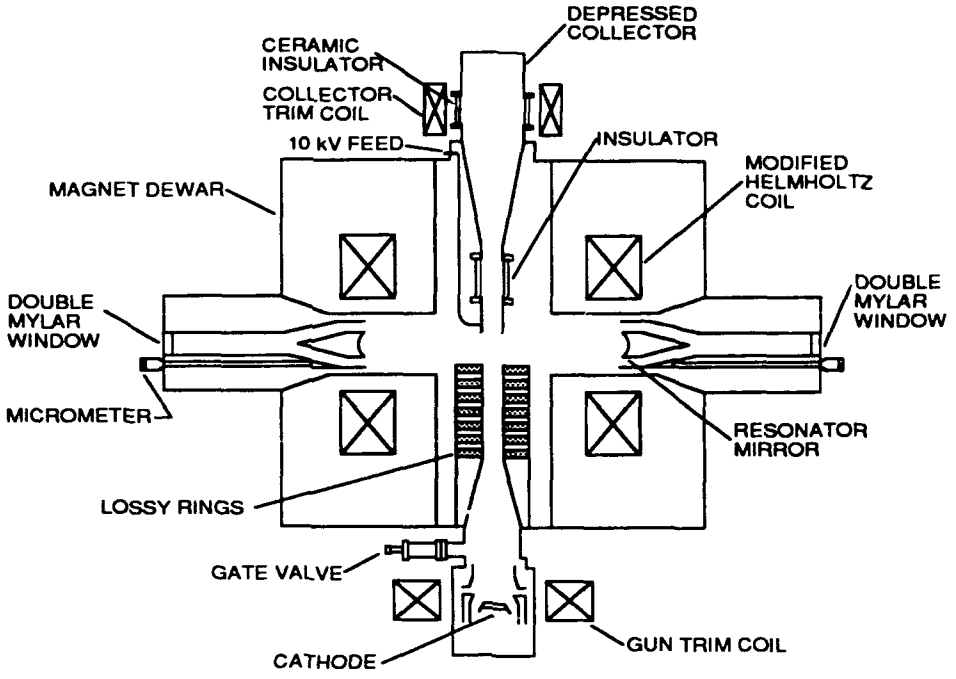

Figure 1: Schematic diagram of the quasioptical gyrotron experiment.

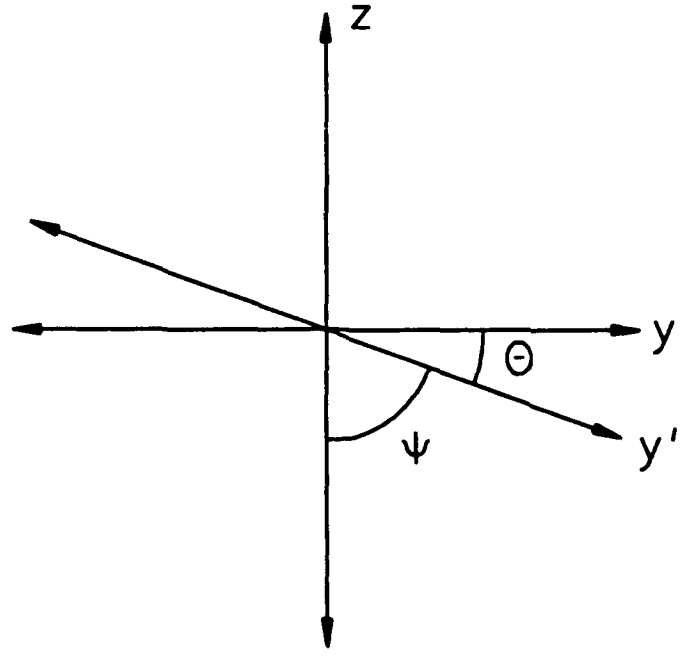

Figure 2: Orientation of the resonator (y')-axis with respect to the electron beam (z)-axis.

wave in the cavity may be expressed as

$$\mathbf{E} = \hat{x} E^t \tag{1}$$

where the physical electric field is obtained by taking the real part of $\mathbf{E}$, and

$$\begin{aligned} E^t_{m,n,l}(x,y',z',t) &= \frac{E_{o,l}}{2}\frac{w_{o,l}}{w_l(y')} H_m\left(\frac{\sqrt{2}x}{w_l(y')}\right) H_n\left(\frac{\sqrt{2}z'}{w_l(y')}\right) \exp\left\{-\frac{\left(x^2+z'^2\right)}{w_l^2(y')}\right\} \\ &\quad \times \exp\left\{-\imath\left[k_l\left(y' + \frac{\left(x^2+z'^2\right)}{2R_w(y')}\right) - \omega_l t \right.\right. \\ &\quad \left.\left. -(m+n+1)\arctan\left(\frac{y'}{z_o}\right)\right]\right\} \end{aligned} \tag{2}$$

where H_m is a Hermite polynomial of order m, w_o is the radiation beam waist,

$$w_l^2(y) = w_{o,l}^2\left(1 + y^2/z_o^2\right), \tag{3}$$

$$R_w(y) = y\left(1 + z_o^2/y^2\right), \tag{4}$$

$$z_o = \frac{\pi w_{o,l}^2}{\lambda} = \frac{d}{2}\left(\frac{1+g}{1-g}\right)^{1/2}, \tag{5}$$

R_w is the radius of curvature of the radiation wavefront, k is the wave number, λ is the wavelength and ω is the angular frequency of the radiation, d is the resonator mirror separation and $g = 1 - d/R_c$, where R_c is the mirror radius of curvature, which is assumed equal to the curvature of the radiation wavefront at the mirror. The electric field of the standing wave in the resonator is obtained by adding the two oppositely directed travelling waves, yielding

$$\begin{aligned} E^s_{m,n,l}(x,y',z',t) &= E_{o,l}\frac{w_{o,l}}{w_l(y')} H_m\left(\frac{\sqrt{2}x}{w_l(y')}\right) H_n\left(\frac{\sqrt{2}z'}{w_l(y')}\right) \exp\left\{-\frac{\left(x^2+z'^2\right)}{w_l^2(y')}\right\} \\ &\quad \times \exp\left\{\imath\left[\omega_l t + (m+n+1)\arctan\left(\frac{y'}{z_o}\right)\right]\right\} \\ &\quad \times \cos\left[k_l\left(y' + \frac{\left(x^2+z'^2\right)}{2R_w(y')}\right) - \frac{l\pi}{2}\right], \end{aligned} \tag{6}$$

where the $l\pi/2$ term in the cosine is necessary to satisfy the boundary conditions at the resonator mirrors.

Of particular interest is the electric field at the electron beam, which is located very near the RF beam waist (i.e. $y' \ll z_o$). In this case $R_w \approx 0$, $w_l(y') \approx w_o$, and $\arctan(y'/z_o) \approx 0$ yielding

$$\begin{aligned} E^s_{m,n,l}(x,y',z',t) &= E_{o,l} H_m\left(\frac{\sqrt{2}x}{w_{o,l}}\right) H_n\left(\frac{\sqrt{2}z'}{w_{o,l}}\right) \exp\left\{-\frac{\left(x^2+z'^2\right)}{w^2_{o,l}}\right\} \\ &\quad \times \exp\{\imath\omega_l t\} \cos\left(k_l y' - \frac{l\pi}{2}\right). \end{aligned} \tag{7}$$

For the $\mathrm{TEM}_{0,0,l}$ mode this becomes

$$E^s_{0,0,l}(x,y',z',t) = E_{o,l} \exp\left\{-\frac{\left(x^2+z'^2\right)}{w^2_{o,l}}\right\} \exp\{\imath\omega_l t\} \cos\left(k_l y' - \frac{l\pi}{2}\right). \tag{8}$$

The peak electric field of the $\mathrm{TEM}_{0,0,l}$ mode along the resonator (y'-) axis is (in MKS units)

$$\begin{aligned} E_{\mathrm{peak}} &= E_{o,l}\frac{w_{o,l}}{w_l(y')} \\ &= \frac{m_o c\omega\gamma}{e\beta_\perp^{s-4}} \frac{w_{o,l}}{w_l(y')} \left(\frac{\sin^2(\psi)}{(1-\beta_{||}\cos(\psi))^2}\right)\left(\frac{2^{s-1}s!}{s^s}\right) F \end{aligned} \tag{9}$$

where F is the peak normalized wave amplitude commonly used in the gyrotron literature,[8, 9] m_o and e are the rest mass and charge (magnitude) of an electron, γ is the relativistic factor, and $\beta_\perp$ and $\beta_{||}$ are the electrons velocity perpendicular and parallel to the magnetic field normalized to c, the speed of light. The parameter s is the harmonic number of the beam–wave interaction for the case of the QOG and should be set to unity for the IREC maser resonator. The angle ψ is the angle between the resonator and electron beam axes, and should be set to $\pi/2$ for the QOG.

III. Ohmic Power Losses

To calculate the ohmic power lost in the resonator mirrors, consider a plane wave incident on a semi-infinite planar conductor as shown in Fig. 3. Assuming that all field quantities $\mathcal{S}$ vary in time as

$$\mathcal{S}(\mathbf{x},t) = \mathbf{S}(\mathbf{x})e^{\imath\omega t} \tag{10}$$

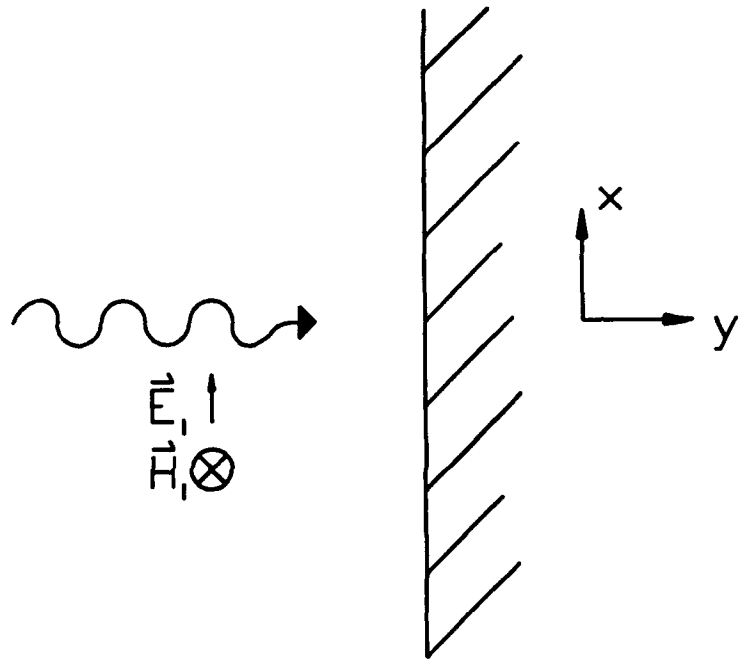

Figure 3: A plane wave incident on a semi-infinite planar conductor.

and

$$\mathbf{B} = \mu\mathbf{H} \tag{11}$$

$$\mathbf{D} = \epsilon\mathbf{E} \tag{12}$$

$$\rho = 0 \tag{13}$$

$$\mathbf{J} = \sigma\mathbf{E}, \tag{14}$$

Maxwell's equations become

$$\nabla \times \mathbf{E} = -i\omega\mathbf{B} \tag{15}$$

$$\nabla \times \mathbf{H} = (i\omega\epsilon + \sigma)\,\mathbf{E} \tag{16}$$

$$\nabla \cdot \mathbf{D} = 0 \tag{17}$$

$$\nabla \cdot \mathbf{B} = 0\,. \tag{18}$$

Using a vector identity we obtain

$$\nabla \times \nabla \times \mathbf{E} = \nabla(\nabla \cdot \mathbf{E}) - \nabla^2\mathbf{E} \tag{19}$$

$$= -\nabla^2 \mathbf{E} \tag{20}$$

$$= -i\omega\mu\nabla \times \mathbf{H}, \tag{21}$$

from which the wave equation follows:

$$\nabla^2 \mathbf{E} = i\omega\mu\left(i\omega\epsilon + \sigma\right)\mathbf{E}. \tag{22}$$

Similarly, one may derive the wave equation for $\mathbf{H}$

$$\nabla^2 \mathbf{H} = i\omega\mu\left(i\omega\epsilon + \sigma\right)\mathbf{H}. \tag{23}$$

Region 1 (see Fig. 3) is free space, so that $\sigma = 0$, leading to

$$\nabla^2 \mathbf{E_1} = -\omega^2 \mu_o \epsilon_o \mathbf{E_1}. \tag{24}$$

Picking the orientation of the electric field

$$\mathbf{E_1} = \hat{x} E_1(\mathbf{x}), \tag{25}$$

the solution to Eq.(24) is

$$\mathbf{E_1} = \hat{x}\left\{E_1^+ e^{-iky} + E_1^- e^{iky}\right\} \tag{26}$$

where

$$k^2 \equiv \omega^2 \mu_o \epsilon_o \ . \tag{27}$$

In region 2 we assume $\omega\epsilon \ll \sigma$ (i.e. the displacement current is negligible) yielding the wave equation

$$\nabla^2 \mathbf{E_2} = i\omega\mu\sigma\mathbf{E_2} \equiv \tau^2 \mathbf{E_2} \tag{28}$$

where

$$\tau \equiv \frac{1+i}{\delta} = (1+i)\left(\frac{\omega\mu\sigma}{2}\right)^{1/2} \tag{29}$$

where δ is the skin depth of the conductor. The solution to Eq.(28) is then

$$\mathbf{E_2} = \hat{x}\left\{E_2^+ e^{-\tau y} + E_2^- e^{\tau y}\right\} \tag{30}$$

$$= \hat{x} E_2^+ e^{-\tau y} \tag{31}$$

since the electric field must be finite at $y \to \infty$. From Eq.(16) we have

$$\nabla \times \mathbf{H}_2 = \sigma \mathbf{E_2} = \hat{x}\sigma E_2^+ e^{-\tau y} \ . \tag{32}$$

Therefore

$$\mathbf{H_2} = \hat{y} H_y(z) + \hat{z} H_z(y) = \hat{z} H_2^+ e^{-\tau y} \tag{33}$$

where

$$H_2^+ = -\frac{\sigma}{\tau} E_2^+ \tag{34}$$

and $H_y(z) = 0$ since there is no z dependence. Applying the boundary equation that the tangential part of the electric field is continuous at the conductor surface yields

$$E_2^+ = E_1^+ + E_1^- \tag{35}$$

$$H_2^+ = -\frac{\delta\sigma\,(1-i)}{2}\left(E_1^+ + E_1^-\right) \ . \tag{36}$$

Again using Eq.(16), we have for the individual plane waves travelling to the right and to the left in region 1,

$$H_1^+ = -\left(\frac{\epsilon_o}{\mu_o}\right)^{1/2} E_1^+ \tag{37}$$

$$H_1^- = \left(\frac{\epsilon_o}{\mu_o}\right)^{1/2} E_1^- \ , \tag{38}$$

and therefore

$$\mathbf{H_1} = \hat{z}\left(H_1^+ e^{-iky} + H_1^- e^{iky}\right) \ . \tag{39}$$

Applying this to the boundary condition that the tangential part of the magnetic intensity must be continuous yields

$$H_2^+ = H_1^+ + H_1^- = -\left(\frac{\epsilon_o}{\mu_o}\right)^{1/2}\left(E_1^+ - E_1^-\right) \ . \tag{40}$$

Using Eq.(36) and more algebra

$$E_2^+ = E_1^+ + E_1^- = \frac{4E_1^+}{2 + \sigma\delta Z_o\,(1-i)} \tag{41}$$

where $Z_o = (\mu_o/\epsilon_o)^{(1/2)}$ is the impedance of free space.

The time averaged power per unit area lost in the conductor (ρ_Ω) is given by the real part of the Poynting vector ($\mathbf{N}$) evaluated at $x = 0$;

$$\rho_\Omega = \Re\left\{\langle \mathbf{N} \rangle|_{x=0}\right\} \tag{42}$$

where

$$\begin{aligned} \langle \mathbf{N} \rangle|_{x=0} &= \frac{1}{2}\mathbf{E_2} \times \mathbf{H_2^*} && (43) \\ &= \hat{y}\frac{\sigma\delta}{4}(1+i)\left|E_2^+\right|^2 && (44) \\ &= \hat{y}\frac{4(1+i)E_1^{+^2}}{\sigma\delta\left[(\mathrm{Z}_o + 2/\sigma\delta)^2 + \mathrm{Z}_o^2\right]} && (45) \end{aligned}$$

For reasonably good conductors and frequencies not too high, the factor

$$\frac{2}{\sigma\delta} = \left(\frac{2\omega\mu_o}{\sigma}\right)^{1/2} \tag{46}$$

is small compared to Z_o ($= 377\Omega$) and the heating density becomes

$$\rho_\Omega = \frac{\left(2E_1^+\right)^2}{2\sigma\delta\mathrm{Z}_o^2}\ . \tag{47}$$

In addition to being applicable to the case of a plane conductor, this equation is a good estimate of the heating density for a curved conductor when the radius of curvature is much larger than the wavelength of the radiation. Using Eq.(2) for a $\mathrm{TEM}_{0,0,l}$ mode at the mirror we have

$$2E_1^+ = E_{o,l}\frac{w_{o,l}}{w_l(d/2)}\exp\left\{-r^2/w_l^2(d/2)\right\}\ . \tag{48}$$

Therefore, the power lost per mirror due to ohmic heating in a mirror of radius a at position d is

$$\begin{aligned} P_{\mathrm{lost_{mirror}}} &= \int_0^a \rho_\Omega 2\pi r\, dr \\ &= \frac{\pi E_{o,l}^2 w_{o,l}^2}{4\sigma\delta Z_o^2}\left[1 - \exp\left(\frac{-2a^2}{w_l^2(d/2)}\right)\right]\ . && (49) \end{aligned}$$

IV. Stored Energy

In vacuum, the time-averaged energy density is

$$u = \frac{1}{4}\left(\mathbf{E}\cdot\mathbf{D}^* + \mathbf{B}\cdot\mathbf{H}^*\right) = \frac{1}{2}\mathbf{E}\cdot\mathbf{D}^* \tag{50}$$

The total stored energy in the resonator is twice the stored energy due to the wave travelling in one direction given by Eq.(2). For a $\mathrm{TEM}_{0,0,l}$ mode this yields

$$\begin{aligned} E_{\text{stored}} &= \frac{\epsilon_o w_{o,l}^2 E_{o,l}^2}{4}\int_{-d/2}^{d/2} dy \int_0^a \frac{2\pi r\, dr}{w_l^2(y)} e^{-2r^2/w_l^2(y)} \\ &= \frac{\pi\epsilon_o E_{o,l}^2 w_{o,l}^2 d}{8}\left[1-\exp\left(\frac{-2a^2}{w_l^2(d/2)}\right)\right] . \end{aligned} \tag{51}$$

V. Ohmic Q

The ohmic Q of a cavity is defined as

$$Q_\Omega = \frac{\omega E_{\text{stored}}}{P_{\text{lost}}} . \tag{52}$$

Noting that power is lost in two mirrors, and using Eqs.(49) and (51) we obtain

$$Q_\Omega = \frac{d}{2}\left(\pi f \mu_o \sigma\right)^{1/2} \tag{53}$$

where f is the frequency of the radiation.

VI. Resonator Heating

In this section we wish to calculate the time dependent rise in temperature of the resonator mirrors. To do so, we solve the one-dimensional heat equation with appropriate boundary conditions[11]:

$$u_t(x,t) - \alpha u_{xx}(x,t) = \frac{A}{\rho c_v} \tag{54}$$

$$u(x,0) = u_o \tag{55}$$

$$u_x(0,t) = 0 \tag{56}$$

$$u_x(L,t) = 0 \tag{57}$$

$$A = \mathcal{F}\delta(x) \tag{58}$$

where $u(x,t)$ is the temperature of the mirror at position x and time t, the subscripts of u denote partial derivatives of u, the mirror is located between $x = 0$ and $x = L$, $\mathcal{F}$ is the flux incident on the mirror, and $\alpha = \kappa/(\rho c_\rho)$ where ρ, c_p, and κ are the mass density, heat capacity, and thermal conductivity of the mirror material.

The first step in solving this problem is to set $\mathcal{F} = A = 0$ and separate variables to find the eigenvalues and eigenvectors of the related homogeneous problem. Setting $u = X(x)T(t)$ and denoting derivatives by primes gives

$$\frac{T'}{\alpha T} = \frac{X''}{X} = -\lambda^2 \; . \tag{59}$$

Therefore

$$X'' + \lambda^2 X = 0 \tag{60}$$

$$X'(0) = X'(L) = 0 \tag{61}$$

which has solutions

$$X_n(x) = \cos(\lambda_n x) \quad \lambda_n = \frac{n\pi}{L} \quad n = 0, 1, 2, \ldots \; . \tag{62}$$

Now let $A \neq 0$ and try the solution

$$u(x,t) = \sum_n T_n(t) X_n(x) \; . \tag{63}$$

Multiplying by $u(x,t)$ and integrating yields

$$\begin{cases} T_0(t) = \frac{1}{L}\int_0^L u(x,t)dx \\ T_m(t) = \frac{2}{L}\int_0^L u(x,t)\cos\left(\frac{m\pi x}{L}\right)dx \quad m = 1, 2, \ldots \end{cases} \tag{64}$$

Next we expand

$$A/(\rho c_p) = \sum_n q_n(t) X_n(x) \; . \tag{65}$$

Inserting Eq.(58) gives

$$\begin{cases} q_0 = \frac{\mathcal{F}}{\rho c_p L} \\ q_m = \frac{2\mathcal{F}}{\rho c_p L} \quad m = 1, 2, \ldots \end{cases} \tag{66}$$

Therefore the differential equation reduces to

$$\sum_n X_n \left(T_n' + \alpha\lambda_n^2 T_n - q_n\right) = 0 \tag{67}$$

Table 1: Parameters for the quasioptical IREC maser experiment.

Mode	$TEM_{0,0,l}$
Output power	15 MW
Frequency	280 GHz
Wavelength	1.1 mm
Magnetic field	6 T
Electron beam energy	500 keV
Electron beam current	200 A
F	0.2
$\alpha \equiv \beta_\perp/\beta_\parallel$	0.5
ψ	20°
μ	12

which leads to

$$\begin{cases} u_0 + q_0 t & n = 0 \\ -\frac{q_n}{\lambda_n^2 \alpha}\left[\exp(-\lambda_n^2 \alpha t) - 1\right] & n = 1, 2, \ldots \end{cases} \tag{68}$$

Thus the solution for the mirror temperature is

$$u(x,t) = u_o + \frac{\mathcal{F}t}{\rho c_p L} + \frac{2\mathcal{F}L}{\pi^2 \kappa} \sum_{n=1}^{\infty} \frac{1}{n^2} \cos\left(\frac{n\pi x}{L}\right)\left[1 - \exp\left(\frac{-n^2\pi^2 \alpha t}{L^2}\right)\right] . \tag{69}$$

VII. The IREC Maser Resonator

In this section the formulae derived will be applied to the current design of the resonator for the quasioptical IREC maser experiment. Representative experimental parameters are given in Table 1. The theory necessary to optimize an IREC maser design is complicated and will be addressed in future publications, however, let us pick $F = 0.2$ for this example. This value is approximately twice the F value for optimum efficiency operation in a QOG and is appropriate for the IREC maser since here the beam electrons interact only with

the RF fields propagating in the direction of the electron beam travel. Also picked are values for the angle between the resonator and electron axes $\psi = 20°$ and the normalized interaction length $\mu = 12$. Specifying the peak heating density at the mirror to be 150 kW/cm^2 determines the resonator mirror separation (81 cm) and radius of curvature (52 cm). The output coupling of 14% is picked to balance the input and output power levels and determines the mirror radius of 3.0 cm. Assuming values for the conductivity (3.6×10^7 siemens/m) and the skin depth (1.6×10^{-7} m), appropriate for copper, Eq.(49) may be used to calculate the power lost per mirror (780 kW).

With the resonator parameters specified, it is a simple matter to apply the derived formulae to obtain the peak electric field at the center of the resonator (Eq.(9)) E_o = 1.1 MV/cm. Similarly, the energy stored in the resonator (Eq.(51)) is $E_{\text{stored}} = 2.4$ J, and the ohmic quality factor (Eq.(53)) is $Q_\Omega = 2.5 \times 10^6$. The resonator heating is calculated assuming that the incident flux is $\mathcal{F} = 150$ kW/cm^2, the peak heating density. Eq.(69) then gives a temperature rise at the surface of the mirror of approximately 150°C for a 2 μsec pulse. Standard values for copper of $\rho = 8.93$ g/cm^3, $c_p = 0.385$ J/(g°K), $\kappa = 3.5$ W/cm°K, $\alpha = 1.02$ cm^2/sec, and a mirror thickness of $L = 1$ cm were used in this calculation. It should be noted that the number of terms necessary for the convergence of the sum in Eq.(69) is approximately 1000. Figure 4 shows that at the end of 2 μsec the temperature rise in the mirror is confined to very near its surface. The parameters calculated for the IREC maser resonator are summarized in Table 2.

VIII. Acknowledgements

We thank Drs. Arne Fliflet and Wallace Manheimer for their helpful discussions. This work was supported by the Office of Fusion Energy of the U.S. Department of Energy and by the Office of Naval Research.

Table 2: Calculated parameters for the quasioptical IREC maser experiment.

Mirror separation (d)	81 cm
Mirror radius of curvature	52 cm
Output coupling	14 %
Mirror radius	3.0 cm
E_o	1.1 MV/cm
w_o	8.5 mm
$w(d/2)$	1.8 cm
z_o	21 cm
Quality factor (diffraction, Q_{diff})	66,000
Quality factor (ohmic, Q_Ω)	2.5×10^6
$\rho_{\Omega_{\text{peak}}}$	150 kW/cm^2
Ohmic power lost (per mirror)	780 kW

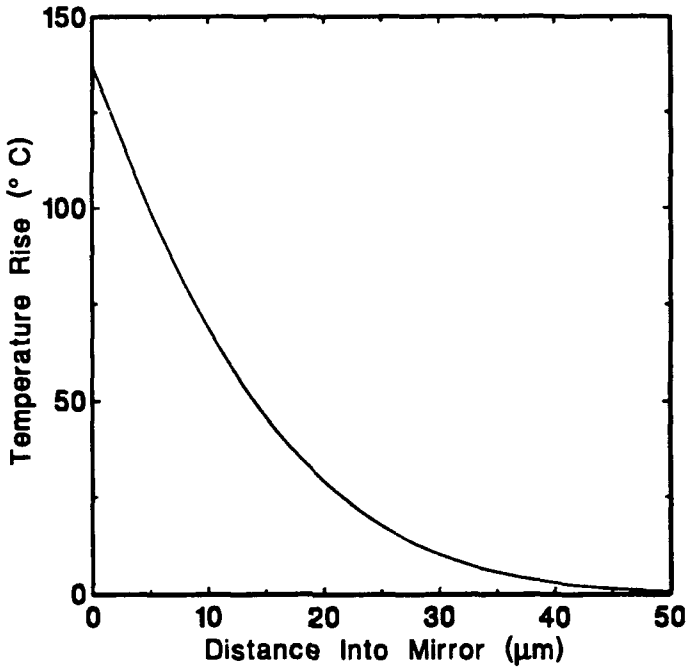

Figure 4: Temperature rise in the resonator mirror calculated from a one-dimensional model for an incident power flux ($\mathcal{F}$) of 150 kW/cm^2 and a 2 μsec pulse length.

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