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Microwave Coupling in EBT Reactor

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DEPARTMENT OF ENERGY

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MICROWAVE COUPLING IN EBT REACTOR

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ABSTRACT

For a typical size ELMO Bumpy Torus (EBT) reactor (~ 1000 MWe), microwave frequencies required lie in the range of 60-110 GHz at power levels of 50-75 MW. As the frequency rises, the unloaded cavity (i.e., without plasma) quality factor Q decreases. Because of the short wavelengths of microwave heating power and the large cavity dimensions of a reactor, it is possible to apply quasi-optical principles in the efficient coupling of power to the plasma. The use of a confocal Fabry-Perot resonator with spherical mirrors is discussed; these serve to confine the microwave power to the region occupied by the plasma. The potential advantages of these resonators include high efficiency utilization of microwave power, minimal thermal burden on the cryopumping system, and significant benefit in preventing microwave leakage from the device. An estimation of the unloaded cavity quality factor Q and the design considerations of Fabry-Perot resonator are given.

INTRODUCTION

The EBT has many promising features as a fusion reactor. These include steady-state operation, large aspect ratio, modularity, easy access for maintenance, relatively simple engineering design requirements, absence of disruptions and toroidal plasma current, and potential availability of several heating options.¹ The heating of an EBT reactor plasma by microwaves and neutral beams has been studied.² In experiments EBT-I and EBT-S,³ electron cyclotron heating (ECH) has been used for heating of the toroidal plasma and for formation of the hot electron rings. The heating is a result of electron cyclotron damping at the resonance surface. Details of the heating mechanism in the present EBT experiments are given in Ref. 4.

After the plasma in a reactor is heated to ignition, the toroidal (bulk) plasma heating will be turned off. The ring heating will, however, have to be sustained throughout the steady-state operation because these hot electron rings are essential for the stable operation of EBT. The microwave frequencies required lie in the range of 60-110 GHz for power

levels of 50-75 MW for a typical size EBT reactor (~ 1000 MWe).¹ Except for the power levels, these frequencies are similar to those planned for future EBT experiments (EBT-P).⁵ Multimegawatt, continuous wave (cw) ECH systems at these frequencies are presently beyond the state of the art for microwave tubes. However, an intensive development program for the EBT-P experiments has been undertaken through subcontracts with private industry.

High power microwave systems for a reactor will include the following elements:

- (a) a multiple array of active devices for the conversion of dc power to microwave power;
- (b) microwave transmission and coupling systems for the efficient transfer of energy to the fusion device; and
- (c) supporting subsystems for overall system control, monitoring, operation, and safety.

Although detailed study in each of these areas is required, we concentrate on the question of microwave coupling in this paper.

The microwave coupling system discussed here is based on the use of quasi-optical methods. Because of the large waveguide cross section, which is determined by voltage breakdown considerations, and because of the existence of a very large number of possible electromagnetic (EM) propagating modes at high frequencies, conventional waveguide techniques are difficult to apply. Fabry-Perot resonators are studied as a possible means of overcoming this problem in the efficient coupling of the power to the plasma.

Estimations of the unloaded cavity quality factor Q for a conventional type cavity and for Fabry-Perot resonators are discussed in the following section. The potential advantages of these resonators, a general procedure for designing them, and the EM field distribution are also given.

CAVITY QUALITY FACTOR Q

The unloaded cavity quality factor Q is defined as

$$Q = \omega \frac{\text{stored energy}}{\text{dissipated power}} . \quad (1)$$

Because of power economy considerations, the Q of the cavity is important. This can be seen from the following relationship⁶ (which can also be derived from impedance-matching considerations):

$$\frac{P_T}{P_O} \cong \left(1 - \frac{Q_L}{Q}\right)^{1/2} , \quad (2)$$

where

P_T = transmitted power through the resonator at resonance,

P_O = power supplied by the source (microwave tube),

Q = unloaded cavity quality factor,

and

Q_L = effective, loaded, quality factor.

Here, Q_L is defined as

$$Q_L^{-1} = Q^{-1} + Q_p^{-1} , \quad (3)$$

where Q_p is due to the plasma in the cavity. In order to maximize P_T/P_O , one should have

$$Q \gg Q_p \sim Q_L . \quad (4)$$

In general, the unloaded quality factor for a conventional closed metallic cavity is given by⁷

$$Q \cong F \frac{\lambda}{\delta_s}, \quad (5)$$

where F is the "form factor" that depends on the shape and mode of the cavity. To a first approximation,⁷ $F \cong (1/\lambda)V/S$, with V and S being the volume and area of the bounding surface of the cavity. In Eq. (5), λ is the wavelength of the resonance frequency, and

$$\delta_s = \sqrt{\frac{2}{\omega \mu_o \sigma}} \quad (6)$$

is the skin depth, where $\mu_o = 4\pi \times 10^{-7}$ H/m and σ is the conductivity of the material. At millimeter and shorter wavelengths, the quantity Q decreases as $\omega^{-1/2}$.

The plasma quality factor Q_p for the EBT geometry and confinement properties can be given by⁸

$$Q_p \cong 2 \frac{V_c}{V_p} \left[\frac{f f_o}{f_p^2} \left(\frac{M - M_r}{1 + M} \right) \right], \quad (7)$$

where

f = heating frequency,

f_o = electron gyrofrequency (average),

f_p = electron plasma frequency,

M = mirror ratio of the vacuum field,

M_r = mirror ratio at the resonance surface ($\cong \sqrt{M}$),

V_c = resonant cavity volume,

and

V_p = plasma volume.

For typical reactor parameters,¹ $Q_p < 10$. Because of the constancy of most of the dimensionless parameters of EBT's,¹ the value in square brackets in Eq. (7) does not change drastically from EBT-I to an EBT reactor; thus,

$$Q_p \cong (\text{constant}) \left(\frac{V_c}{V_p} \right). \quad (7a)$$

In order to maximize efficient utilization of microwave power, the following requirements are imposed:

- (a) Q , the unloaded cavity quality factor, should be very high; and
- (b) Q_p for the plasma should be low enough that $Q_L \cong Q_p \ll Q$. Equation (2) then becomes

$$\frac{P_T}{P_0} \cong 1 - \frac{1}{2} \frac{Q_p}{Q}. \quad (8)$$

The above conditions on the value of Q are not easily satisfied by the conventional type of cavity completely bounded by metallic surfaces at high frequencies and large V_c/V_p .

MICROWAVE COUPLING CONSIDERATIONS

Because of the short wavelengths of microwave heating power and the large cavity dimensions of a reactor (and future devices), possibilities exist for application of quasi-optical principles in the coupling of power to the plasma. Suitably shaped reflecting surfaces and baffles inside the vacuum volume can confine the microwave power to the region occupied by the plasma. Such an arrangement is an open Fabry-Perot resonator. Basically, a microwave Fabry-Perot resonator is formed by two conducting mirrors (reflectors) separated by an arbitrary distance that is only partially enclosed [i.e., V_c/V_p (of F-P resonator) $< V_c/V_p$ (of conventional cavity)]. There are several subclasses of these resonators; they are characterized by the type of mirror used (plane,

paraboloidal, or spherical) and by the spacing between the mirrors. The one most suitable for EBT is a confocal Fabry-Perot resonator with spherical mirrors. The potential advantages of these resonators, which will be discussed in the next section, include high efficiency utilization of microwave power, minimal I^2R thermal burden on the cryopumping system produced by microwave losses, and a significant benefit in preventing microwave leakage from the device. Residual microwave power that escapes from the open resonator system can be dissipated by suitably cooled lossy surfaces within the vacuum system. In this way, high-Q resonances within the vacuum chamber can be avoided, voltage breakdown and arcing problems eliminated, and the possibility of microwave leakage further reduced.

Preliminary design considerations of the confocal Fabry-Perot resonator are given in the next section. It should be noted that the development of compatible quasi-optical microwave transmission, distribution, and coupling systems for operation at very high power levels and short wavelengths requires a detailed research and development effort as well as experiment and demonstration.

DESIGN CONSIDERATIONS OF FABRY-PEROT RESONATOR

The spherical mirror resonator is the most common type in use in laser and millimeter wave applications because of its superior alignment properties. Here, we will discuss a confocal Fabry-Perot resonator with spherical mirrors. In a confocal resonator, the mirrors are spaced in such a way that the distance between the mirrors, $d \gg \lambda$, is equal to the radius of curvature of the mirrors, R , i.e., the focal points of the mirrors coincide (see Fig. 1). This mirror spacing gives the minimum mode volume,⁹ which is defined as the half-power width of the field at the mirror multiplied by the spacing of the mirrors (see Fig. 1). This means that the fields are fairly well concentrated near the axis for the entire length of the confocal resonator. The confocal geometry also has an advantage in that the mirror reflections are self-correcting.

The computation of the EM field in the resonator has been studied in great detail elsewhere.¹⁰ The field pattern can be obtained through

R = RADIUS OF CURVATURE ($=d$)

d = SPACING OF THE MIRRORS

a_s, a_m = HALF POWER RADIUS FOR MIRRORS ($a_m = \sqrt{2} a_s$)

r_m = MIRROR RADIUS

Fig. 1. Geometry of confocal resonator with spherical mirrors.

the Maxwell equations. The modes of the resonator are represented by TEM_{lpq} , where l , p , and q are all integers. The subscriptions l and p refer to the transverse variations of the electric and magnetic fields, and q equals the number of half wavelengths between the mirrors (in the z direction in Fig. 1). In cylindrical coordinates (r, ϕ, z) , the relative field distribution at the reflectors ($z = \pm d/2$) of a TEM_{lpq} mode can be written as^{10,11}

$$\frac{E(r, \phi, \pm d/2)}{E_0} = \mu^l L_p^l(\mu^2) e^{-\mu^2/2} \cos l\phi, \quad (9)$$

where

$$\mu^2 = (r/a_s)^2$$

$$L_p^l = \text{associated Laguerre polynomials.}$$

Here, a_s represents the spot size at the center for the fundamental mode TEM_{00q} and is given by

$$a_s = \frac{a_m}{\sqrt{2}} = \sqrt{\frac{\lambda d}{2\pi}} \quad (\text{see Fig. 1}). \quad (10)$$

The modes here have negligible axial electric and magnetic fields, i.e., $E_z = B_z \cong 0$. In the low-loss mode, $l = p = 0$, the electric field is essentially transverse and shows a simple Gaussian decay of intensity in the radial direction.

The condition for resonance for the TEM_{lpq} mode (for the confocal resonator) is given by¹⁰

$$\frac{4d}{\lambda} = 2q + (1 + l + 2p). \quad (11)$$

As seen from Eq. (11), there is a considerable degeneracy of modes (i.e., many different values of l , p , and q give the same resonant frequency). However, the higher order degenerate modes are relatively

unimportant because of their large diffraction losses (i.e., they are highly damped, effectively leaving energy only in the lower order modes reflecting between the mirrors). Essentially single-mode operation is possible by exciting the resonator through a small hole(s) at the center of the mirror and by taking advantage of the symmetry of the modes. The mode that is excited in this way has $l = p = 0$ and is the lowest loss mode with the resonance condition

$$\frac{4d}{\lambda} = 2q + 1 . \quad (12)$$

It should be noted that the low-loss mode of this resonator is simultaneously resonant at all odd harmonics of the driving microwave frequency.

The theoretical unloaded Q value of the Fabry-Perot resonator is given by⁹

$$Q = 2\pi f \frac{\text{energy stored}}{(\text{energy loss/transit})(\text{No. transit/cycle})} = \frac{\omega d}{\alpha c} = \frac{2\pi}{\lambda} \frac{d}{\alpha} , \quad (13)$$

where α is the fractional power loss per mirror reflection. The major factors contributing to this unloaded resonator Q are the reflection losses α_R , due to the finite conductivity of the mirror, and diffraction losses α_D . The total fractional power loss α is then

$$\alpha = \alpha_D + \alpha_R . \quad (14)$$

Reflection losses. Reflection losses result from the absorption in the reflectors and the transmission through them due to the finite conductivity σ of the mirrors. Hence, α_R can be written in terms of the reflection coefficient Γ of the mirror:⁹

$$\alpha_R = 1 - |\Gamma|^2 \cong 2 \left(\frac{2\varepsilon_0 \omega}{\sigma} \right)^{1/2} = 4\pi \left(\frac{\delta_s}{\lambda} \right) . \quad (15)$$

For stainless steel, $\sigma = 1.66 \times 10^6$ mho/m, and for aluminum, $\sigma = 3.54 \times 10^7$ mho/m. At 110 GHz, one obtains $\alpha_R(\text{stainless steel}) \cong 5.32 \times 10^{-3}$ and $\alpha_R(\text{aluminum}) \cong 1.15 \times 10^{-3}$.

Diffraction losses. The diffraction losses result from the finite aperture of the reflectors and from imperfections in their "flatness." It should be pointed out that the diffraction losses for the spherical confocal Fabry-Perot resonators are orders of magnitude smaller than they are for the plane-parallel type. For the confocal resonators with a circular mirror, α_D is given by¹¹

$$(\alpha_D)_{lp} \cong \frac{2\pi(8\pi N)^{2p+l+1} e^{-4\pi N}}{p!(p+l+1)!}, \quad N \gg 1, \quad (16)$$

where

$$N = \frac{r_m^2}{\lambda d} \quad (17)$$

is the Fresnel number and r_m is the mirror radius (see Fig. 1). For the low-loss mode $l = p = 0$, and for $N \gg 1$,

$$\alpha_D \cong 16\pi^2 N \exp(-4\pi N). \quad (18)$$

By proper size selection for the mirrors (i.e., r_m), α_D can be made quite small with respect to α_R and thus may be neglected. In the case $\alpha_D \ll \alpha_R$, Eq. (13) becomes

$$Q \cong \frac{2\pi}{\alpha_R} \frac{d}{\lambda}. \quad (19)$$

In comparing Eqs. (5) and (19), one can see that the unloaded Q value of the Fabry-Perot resonator is larger than the unloaded Q value of the conventional cavity.

A simple general procedure for designing a confocal resonator could then be summarized as follows.

- (a) The mirror spacing d can be estimated from the dimensions of the system ($d >$ plasma diameter).
- (b) Reflection losses α_R can be calculated for a given applied microwave frequency and for a choice of material from Eq. (15).
- (c) In order to neglect the diffraction losses and simplify the calculations, α_D should be made much smaller than α_R . For example, one can set $\alpha_D \cong 0.01 \alpha_R$.
- (d) Given α_D from (c), the Fresnel number can be obtained from Eq. (18) for the low-loss mode. It should be noted that N should be much greater than one in order to use Eq. (18).
- (e) Given N from (d), the required mirror radius r_m can be calculated from Eq. (17).

It is necessary to point out that the calculated mirror radius r_m should be at least $10-30\lambda$ and that the mirror spacing $d(=R)$ should be at least $50-75\lambda$, in order to use the given equations under realistic assumptions. A simple exercise can show that for the frequency ranges required in an EBT reactor (60-110 GHz), the wavelength λ is in the range of 2.5-5 mm, which the above requirements can easily satisfy.

No attempt has been made here to give any specific design parameters for a reactor or for future fusion devices. Although the calculations and method suggested in this paper are straightforward within the validity of the assumptions given, integrated study is needed for the overall microwave system components mentioned in the introduction in order to make plausible design estimates.

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