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**DESIGN OF THE WAVEGUIDE FOR MICROWAVE HEATING
OF SOLID LITHIUM CERAMIC BLANKETS**

by

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Fusion Power Program

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ABSTRACT

A description is given of the design of a dielectric-loaded waveguide for thermohydraulic testing of solid ceramic tritium breeder material in a non-nuclear environment. The dielectric-loaded waveguide provides uniform heating over module surfaces that would face a fusion reactor plasma and simulates the exponential power decay characteristic of the neutron flux over the high power region of the blankets. A 200-MHz design suitable for modules with cross section of up to 20×40 cm is presented.

1. INTRODUCTION

The expected thermo-mechanical environment for a breeding blanket in a fusion reactor is expected to be more severe than any that exists today.⁽¹⁻³⁾ The present design studies rely on the extrapolation of existing data and empirical correlations. Adequate supporting data on component behavior is essential to the future technology program. It is desirable to develop some of the supporting data in a non-nuclear environment where hands-on study is possible. The dielectric-loaded-waveguide described in this report is designed to simulate the power profile in a solid lithium breeder blanket that would be generated by the neutron flux of a fusion power reactor.

Two of the solid ceramic breeder materials considered are LiO_2 and $\gamma\text{-LiAlO}_2$. They would be configured in a module of the type shown in Fig. 1.

Fig. 1. Solid breeder blanket module.

The rear of the blanket module is the top surface and the front of the module is the bottom surface of the isometric drawing shown in Fig. 1. The cooling tubes run through the module in a plane parallel to the top and bottom surfaces. Designating these surfaces as x-y planes, the heat generated by the neutrons is uniform in an x-y plane and decreases from the bottom surface with the $\exp(-\alpha z)$ where α is about 8.8 m^{-1} and z is in the direction from the bottom surface to the top. The heat generation at the bottom surface of the module would be about 24 W/cc for a 2 MW/m^2 reactor flux.

Thus, the waveguide must provide uniform heating over an x-y plane with decreasing heat generation in the z direction similar to or with an exponential decay. It must be possible to add cooling tubes without seriously perturbing these heat profiles. The waveguide should be able to handle significantly-sized modules, those approaching nearly full-sized segments.

The type of waveguide suggested for this application is the TEM mode, dielectric-loaded waveguide.⁽⁴⁻⁵⁾ A cross section of the waveguide is shown in Fig. 2.

Fig. 2. Dielectric loaded waveguide configuration.

2. TEM MODE, DIELECTRIC-LOADED WAVEGUIDE

The waveguide shown in Fig. 2 has three regions; the sample region in the center and two dielectric-loaded regions, one on each side of the sample region. The breeder ceramic has a dielectric constant equal to $(\epsilon_s + j\epsilon_l)\epsilon_0$, where ϵ_l is the lossy part of the dielectric constant. The dielectric constant in the loading sections is $(\epsilon_l + j\epsilon_x)\epsilon_0$. It is necessary for $\epsilon_l > \epsilon_s$ to achieve the TEM mode in the sample section. It is also necessary that $\epsilon_l > \epsilon_x$ to achieve good power efficiency. In fact, it is desired that $\epsilon_l \gg \epsilon_x$.

The configuration shown in Fig. 2 has a shorting plate across the waveguide at $z = l$. This produces a standing wave in the sample region. The reason for this will be discussed in the section on heating of the sample. The EM fields for the TEM mode are:

In the region $|x| < a$

$$\begin{aligned} E_y &= E_0 \sin k_z(l - z), \\ H_x &= j \left(\frac{k_z E_0}{\omega \mu_0} \right) \cos k_z(l - z), \\ H_z &= 0. \end{aligned} \quad (1)$$

In the region $-b < x < -a$

$$\begin{aligned} E_y &= E_0 \sin k_x(x + b) \sin k_z(l - z), \\ H_x &= j \left(\frac{k_z E_0}{\omega \mu_0} \right) \sin k_x(x + b) \cos k_z(l - z), \\ H_z &= j \left(\frac{k_x E_0}{\omega \mu_0} \right) \cos k_x(x + b) \sin k_z(l - z). \end{aligned} \quad (2)$$

In the region $a < x < b$

$$\begin{aligned} E_y &= E_0 \sin k_x(b - x) \sin k_z(l - z), \\ H_x &= j \left(\frac{k_z E_0}{\omega \mu_0} \right) \sin k_x(b - x) \cos k_z(l - z), \\ H_z &= -j \left(\frac{k_x E_0}{\omega \mu_0} \right) \cos k_x(b - x) \sin k_z(l - z). \end{aligned} \quad (3)$$

The TEM dielectric-loaded waveguide mode described by Eqs. (1) through (3) exists when the frequency and dimensions are chosen to satisfy the following equations:

$$k_x = \frac{\pi}{2(b-a)}, \quad (4)$$

$$k_z = \omega \sqrt{\mu_0 \epsilon_0 \epsilon_s} \quad (5)$$

and

$$\begin{aligned} \omega^2 \mu_0 \epsilon_1 \epsilon_0 &= k_x^2 + k_z^2, \\ \omega^2 \mu_0 \epsilon_0 (\epsilon_1 - \epsilon_s) &= \left[\frac{\pi}{2(b-a)} \right]^2. \end{aligned} \quad (6)$$

Only the H_x and E_y field components exist in the sample region, $|x| < a$ and $0 < y < d$, and these are uniform in the x-y plane. The cooling tubes extend across the sample in the x-direction, which is a direction that does not seriously interfere with the primary TEM mode since the E_y field is perpendicular and the H_x field is parallel to this conducting boundary. Some local field enhancement will occur in the immediate neighborhood of the conductor, but this will not alter the bulk heating profile by much.

It is possible to design waveguides at a frequency of about 200 MHz that can accommodate sample sections as large as 10 to 20-cm high in the y-direction and some fraction of a meter wide in the x-direction. The limit is determined by the onset of degenerate waveguide modes, some of which could probably be suppressed if somewhat larger sample regions are needed. Of course, the availability of rf power could also become a limiting factor. Heating of the sample section and rf power requirements are discussed in the next section.

The relative dielectric constant, ϵ_s , of LiIO_2 has a value of 2.87. At 200 MHz, the value of k_z , given by Eq. (5), is 7.1. The cross section of the sample is $2ad$. The widths of the dielectric loading sections are $(b-a)$. If Al_2O_3 with a relative dielectric constant of 8.5 is used, $(b-a)$, given by Eq. (6), is 15.8 cm.

3. HEATING OF THE SAMPLE

The microwave power generated per unit volume, P , in the sample is proportional to the imaginary part of the complex permittivity; i.e.,

$$P = 1/2 \omega \epsilon_0 \epsilon_l E_0^2 \sin^2 k_z (l - z). \quad (7)$$

The power per unit volume due to neutron heating, P_n , in the breeder blanket that is to be simulated is,

$$P_n = W_0 e^{-\alpha z}, \quad (8)$$

where

$$\alpha = 8.8 \text{ m}^{-2},$$

and

$$W_0 = 24 \text{ MW/m}^3.$$

By proper choice of the parameters, k , ω , and E_0 , the first two terms of the Taylor expansions of Eqs. (7) and (8) can be made equal, achieving a relatively close approximation to the thermal load desired. Therefore, Eqs. (7) and (8) and the first derivatives of Eqs. (7) and (8) are set equal to each other at some point, z_0 , that leads to the best match

$$1/2 \omega \epsilon_0 \epsilon_l E_0^2 \sin^2 k_z (l - z_0) = W_0 e^{-\alpha z_0}, \quad (9)$$

and

$$k_z \omega \epsilon_0 \epsilon_l E_0^2 \sin k_z (l - z_0) \cos k_z (l - z_0) = \alpha W_0 e^{-\alpha z_0}. \quad (10)$$

Combining Eqs. (9) and (10),

$$2k_z \cos k_z (l - z_0) = \alpha \sin k_z (l - z_0), \quad (11)$$

$$(l - z_0) = \frac{1}{k_z} \arctan \left(\frac{2k_z}{\alpha} \right). \quad (12)$$

The exponential curve is always greater than or equal to the sine-squared curve if you actually set the parameters according to Eqs. (9) through (12). A smaller difference results over the whole range by setting the amplitude, E_0 , of Eq. (7) slightly higher.

The value k_z for LiO_2 is 7.1, therefore, $(l - z_0)$ given by Eq. (12) is 14.3 cm. A quarter wavelength standing wave in the dielectric-loaded waveguide is $\pi/2k_z$, or 22.1 cm. The region of greatest stress and most interest in the breeder material is the first 6 to 10 cm, since in that distance the power deposition has dropped to 50% of the generation of power at the front surface. A sample length, l , of somewhere between 17.3 and 19.3 cm would be required. Figures 3, 4, and 5 show the comparison between the sine-squared and $\exp(-\alpha z)$ profiles for sample lengths of 17.3, 18.3, and 19.3 cm. The first half of the sample region provides a fairly close match between the two curves over the first 6 to 10 cm. the difference is about $\pm 3\%$ for 6 cm, $\pm 6\%$ for 8 cm, and $\pm 9\%$ for nearly 10 cm.

The amplitude of the wave, E_0 , needed to satisfy Eq. (9) is dependent on the imaginary, or lossy, part of the permittivity, ϵ_i . The value of this parameter is not accurately known, but appears to be about 0.01 to 0.001 ϵ_0 .

Fig. 3. Comparison of sine-squared and $\exp(-\alpha z)$ power profiles for the first 6 cm of a 17.3-cm sample length.

Fig. 4. Comparison of sine-squared and $\exp(-\alpha z)$ power profiles for the first 8 cm of an 18.3-cm sample length.

Fig. 5. Comparison of sine-squared and $\exp(-\alpha z)$ power profiles for the first 10 cm of a 19.3-cm sample length.

The peak values of electric field would be 340 kV/m for $\epsilon_L = 0.01 \epsilon_0$ and 1075 kV/m for $\epsilon_L = 0.001 \epsilon_0$. These values are achievable without electrical breakdown problems.

4. MATCHING SECTION

The dielectric-loaded waveguide shown in Fig. 2 must be matched to the rf power source. The preferable way to develop the electric fields calculated in the previous section is to build the shorted waveguide section into a matching cavity that is driven from an excitation loop in the matching section. The evanescent fields at the matching boundary to the sample section must be kept small enough to maintain the power profiles described in Section 3. There are several options which include tapered sections, quarter-wave transformers, etc. The one proposed in this section uses more Al_2O_3 and results in a rather smooth match for sample widths, $2a$, up to 0.2 m, but presupposes that the loss factor of the Al_2O_3 is much better than the loss factor of the LiO_2 and $\gamma\text{-LiAlO}_2$. The indications are that Al_2O_3 material is available that has one to two orders magnitude lower dielectric loss than the LiO_2 and $\gamma\text{-LiAlO}_2$. A top view of the suggested cavity with the sample section and matching section is shown in Fig. 6.

Fig. 6. Top view of the cavity showing the sample section and matching section.

The matching section is a TE_{10} waveguide where the electric field, E_{ym} , for the propagating mode is

$$E_{ym} = E_{1m} \cos \beta x \sin \gamma(z + r) \quad (13)$$

where

$$\beta = \pi/2b ,$$

and

$$\gamma = \sqrt{\omega^2 \mu_0 \epsilon_0 \epsilon_1 - \beta^2} .$$

A complete modal expansion must be done to find the actual fields in the cavity. In the matching section, the fields are:

$$E_{ym} = E_{1m} \cos \beta_1 x \sin \gamma_1(z + l) + \sum_{n=2}^{\infty} E_{nm} \cos \beta_n x e^{\gamma_n z} , \quad (14)$$

$$H_{xm} = -\frac{j\gamma_1 E_{1m}}{\omega\mu_0} \cos \beta_1 x \cos \gamma_1(z + l) + \sum_{n=2}^{\infty} -\frac{j\gamma_n E_{nm}}{\omega\mu_0} \cos \beta_n x e^{\gamma_n z} , \quad (15)$$

and

$$H_{zm} = -\frac{j\beta_1 E_{1m}}{\omega\mu_0} \sin \beta_1 x \sin \gamma_1(z + l) + \sum_{n=2}^{\infty} -\frac{j\beta_n E_{nm}}{\omega\mu_0} \sin \beta_n x e^{\gamma_n z} , \quad (16)$$

where

$$\beta_n = n\pi/2b ,$$

$$\omega^2 \mu_0 \epsilon_0 \epsilon_1 = \beta_n^2 - \gamma_n^2 . \quad (17)$$

In the sample section the fields are:

For $|x| < a$

$$E_{ys} = E_0 \sin k_z(l - z) + \sum_{p=2}^{\infty} E_{ps} \cos \xi_p x e^{-\lambda p z}, \quad (18)$$

$$H_{xs} = \frac{jk_z E_0}{\omega \mu_0} \cos k_z(l - z) + \sum_{p=2}^{\infty} \frac{j \lambda_p E_{ps}}{\omega \mu_0} \cos \xi_p x e^{-\lambda p z}, \quad (19)$$

$$H_{zs} = \sum_{p=2}^{\infty} \frac{j \xi_p E_{ps}}{\omega \mu_0} \sin \xi_p x e^{-\lambda p z}, \quad (20)$$

where

$$\omega^2 \mu_0 \epsilon_0 \epsilon_s = \xi_p^2 - \lambda_p^2. \quad (21)$$

For $-b < x < -a$

$$\begin{aligned} E_{ys} &= E_0 \sin k_x(x + b) \sin k_z(l - z) \\ &+ \sum_{p=2}^{\infty} D_{ps} \sin \eta_p(x + b) e^{-\lambda p z}, \end{aligned} \quad (22)$$

$$\begin{aligned} H_{xs} &= \frac{jk_z E_0}{\omega \mu_0} \sin k_x(x + b) \cos k_z(l - z) \\ &+ \sum_{p=2}^{\infty} \frac{j \lambda_p D_{ps}}{\omega \mu_0} \sin \eta_p(x + b) e^{-\lambda p z}, \end{aligned} \quad (23)$$

$$\begin{aligned} H_{zs} &= \frac{jk_x E_0}{\omega \mu_0} \cos k_x(x + b) \sin k_z(l - z) \\ &+ \sum_{p=2}^{\infty} \frac{j \eta_p D_{ps}}{\omega \mu_0} \cos \eta_p(x + b) e^{-\lambda p z}, \end{aligned} \quad (24)$$

where

$$\omega^2 \mu_0 \epsilon_0 \epsilon_1 = \eta_p^2 - \lambda_p^2 . \quad (25)$$

The equations for the region $a < x < b$ are the mirror images of the equations in the region $-b < x < -a$. It's also necessary that the matching equations at $|x| = (b - a)$ be satisfied; i.e.,

$$D_{ps} \sin \eta_p(b - a) = E_{ps} \cos \xi_p a . \quad (26)$$

and

$$\eta_{ps} D_{ps} \cos \eta_p(b - a) = \xi_p E_{ps} \sin \xi_p a . \quad (27)$$

Matching the field components at the $z = 0$ boundary given by Eqs. (14) through (16) with those of the sample section given by Eqs. (18) through (20) and Eqs. (22) through (24) will lead to the complete solution for the fields in the cavity. The field perturbation due to the higher order modes produce some slight non-uniformity in heating near the $z = 0$ boundary and they are certainly more significant as the sample size increases in the dimension, but for the most part these effects are about 5% or less for $a = 10$ cm.

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