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MASTER

A FOLDED WAVEGUIDE COUPLER FOR ION CYCLOTRON HEATING*

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ABSTRACT

A new type of waveguide coupler for plasma heating in the ion cyclotron range of frequencies is described. The coupler consists of a series of interleaved metallic vanes within a rectangular enclosure analogous to a wide rectangular waveguide that has been "folded" several times. At the mouth of the coupler, a plate is attached which contains coupling apertures in each fold or every other fold of the waveguide, depending upon the wavenumber spectrum desired. This plate serves primarily as a wave field polarizer that converts coupler fields to the polarization of the fast magnetosonic wave within the plasma. Theoretical estimates indicate that the folded waveguide is capable of high-efficiency, multimewatt operation into a plasma. Bench tests have verified the predicted field structure within the waveguide in preparation for high-power tests on the Radio Frequency Test Facility at the Oak Ridge National Laboratory.

INTRODUCTION

Plasma heating in the ion cyclotron range of frequencies (ICRF) has been thoroughly developed over many years in a variety of fusion experiments.¹⁻⁸ Inductive loops have been used most extensively to couple power into the plasma in these experiments. Ridge waveguides,⁹ dielectric loaded waveguides,¹⁰ cavity backed loops,¹¹ and cavity backed aperture antennas¹² have all been proposed for ICRF heating although definitive tests of these devices have yet to be performed on a fusion experiment.

This paper describes a new type of waveguide coupler for plasma heating which is adapted from a concept known as a "folded waveguide" reported by Barrow and Shaevitz in connection with low-frequency waveguide transmission systems.¹³ Extensive coverage of the theory of the folded

waveguide coupler for plasma heating is contained in Refs. 14 and 15. Only a brief summary of the theory will be presented here. The basic idea behind the folded waveguide coupler involves folding a simple rectangular guide whose width is much greater than its height to form a more compact structure. A simplified diagram of this concept is illustrated in Fig. 1. Cutoff for the folded waveguide occurs when the path length around the folds (dashed line in Fig. 1) equals one-half of a free-space wavelength. By adding a large number of folds, the path length around the folds can be made large, leading to very low cutoff frequencies.

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Fig. 1 The folded waveguide concept for reducing the overall size of waveguides. Cutoff occurs when the length of the dashed line around the folds equals half of a free-space wavelength.

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An adjustable shorting plate is placed at the back of the waveguide, and a plate with openings at every fold or every other fold of the structure is placed at the mouth of the waveguide. Fig. 2 shows these additions to the basic folded waveguide structure. The aperture plate largely eliminates the E_z field without greatly affecting the H_z and $E_\perp$ fields which couple to the fastwave. A Faraday shield may be placed within the openings of the aperture plate to further reduce the E_z field. The moveable shorting plate at the back of the coupler adjusts the ratio of E_z to H_z at the mouth of the coupler to match the ratio near the plasma surface.

Fig. 2. The folded waveguide coupler for ICRF heating. A polarizing plate at the mouth of the coupler and a shorting plate $\sim \lambda_g/2$ back from the coupling end of the structure have been added to the basic folded waveguide to produce fields suitable for excitation of the fast magnetosonic wave.

A variation of the simple folded waveguide coupler shown in Fig. 2 is the tapered folded waveguide coupler shown in Fig. 3. In this case the internal vanes within the coupler are tapered between the middle of the coupler and the mouth of the coupler as illustrated in the figure. The apertures can thereby be enlarged to nearly fill the entire port. For a constant total power, the power flux at the plasma/coupler interface will be reduced to nearly half of that found for the simple folded waveguide coupler which uses the "standard polarizing plate" indicated in Fig. 2. A disadvantage of the tapered folded waveguide coupler is that more energy is contained in high-order cavity modes which are cut off. Also, the surface-to-volume ratio is greater than for the untapered coupler. These characteristics will tend to lower the unloaded Q of the cavity somewhat. In addition, TM modes having radial electric fields will be excited by this coupler. The TM fields may couple to surface waves more strongly than the TE fields.

Fig. 3. The tapered folded waveguide coupler.

The principal advantages of the folded waveguide coupler (tapered and untapered) are the low electric fields maintained at the critical plasma/coupler interface, the good match to plasma fast-wave fields, the all-metal construction, and the ability to easily fit between toroidal field coils.

THEORY

A theory for the folded waveguide which yields approximate solutions for the fields within the coupler and external to the coupler is presented in Ref. 14. More precise 3-D finite-element calculations have also been initiated. Preliminary results of the 3-D calculations are presented in Ref. 15. In the approximate calculation in Ref. 14, the folded waveguide is analyzed as an equivalent "unfolded" waveguide with inductive irises at the mouth of the structure to model the shorting diaphragms at the mouth of the folded waveguide coupler.

The region outside the coupler is modeled as a completely enclosed aperture coupled cavity. Fields are calculated assuming perfectly conducting walls. Power absorbed from the plasma is estimated from

$$P = \frac{1}{2} \operatorname{Re}(Z_p) \int_s \left| H_z \right|^2 ds \quad (1)$$

where Z_p is an appropriate plasma surface impedance and the integral is evaluated over the plasma surface.

Using the above procedure, theoretical estimates of coupling efficiency and power handling potential can be made. Table 1 summarizes the various quantities of interest which have been calculated for a folded waveguide suitable for use on the Tore Supra tokamak in Cadarache, France.¹⁶ It is found that extremely low electric fields can be maintained at the critical plasma/coupler interface (less than 2.3 kV/cm at 10 MW and $f = 120$ MHz in the example). Peak voltages occur well back into the coupler where higher electric fields can be tolerated. Coupling efficiencies are quite high (up to 99%) for the examples given. For a Tore Supra size port, folded waveguide couplers are practical even at frequencies of 60 MHz or less. Power handling and coupling efficiency improve as frequency is increased as seen by comparing the 120-MHz example in Table 1 to the 60-MHz example.

Table 1. Tore Supra folded waveguide coupler parameters at 10 MW of input power and 10-cm plasma/coupler separation (Plasma parameters are $n_p = 7.5 \times 10^{13} \text{ cm}^{-3}$, minor radius = 70 cm, $B = 40$ kG. Coupler overall dimensions are 60×70 cm.)

	120-MHz coupler ($\omega/\Omega_H = 2$) (four sections)	60-MHz coupler ($\omega/\Omega_H = 2$) (eight sections)
Electric field in coupling apertures	2.3 kV/cm	1.6 kV/cm
Peak electric field	20 kV/cm	42 kV/cm
Distance from coupler mouth to field peak	72 cm	145 cm
Plasma loaded quality factor	213	904
Unloaded quality factor	23,440	9,770
Coupling efficiency	99%	92%
Coupler length	144.7 cm	291.45 cm
Real part of the plasma surface impedance	114 Ω	73 Ω

A more precise analysis of the waveguide fields has been initiated which uses a 3-D finite-difference technique to compute the full-wave fields and resonance frequency of the exact waveguide geometry. The analysis is based upon the solution of Maxwell's equations. For a source-free, perfectly conducting waveguide, the wave equation solved is

$$\nabla^2 + \mu_0 \epsilon_0 \omega^2 \begin{Bmatrix} \mathbf{E} \\ \mathbf{H} \end{Bmatrix} = 0 \quad (2)$$

The boundary conditions at the perfectly conducting walls are given by

$$\mathbf{n} \times \mathbf{E} = 0 \text{ and } \mathbf{n} \cdot \mathbf{H} = 0 \quad (3)$$

where $\mathbf{n}$ is the unit vector normal to the surface of the boundary. A contour plot of H_z (toroidal H) for the fundamental TE propagating mode of the folded waveguide is shown in Fig. 4. The dashed lines in the figure indicate a reversal in the direction of the field relative to the field in regions containing solid lines. The field is found to reverse

Fig. 4. Contour plot of the toroidal magnetic field of the wave for a four-section coupler similar to that displayed in Fig. 2. Equal amplitude increments occur between lines. Dashed lines indicate a reversal of sign.

in adjacent folds of the structure as expected from a consideration of the unfolded equivalent waveguide fields.

FREE-SPACE MEASUREMENTS

Low-power tests have been conducted on a folded waveguide cavity to verify the predicted free-space field pattern within the structure and to test possible impedance matching schemes. A small-scale version was used in the test having four internal sections similar to the folded waveguide illustrated in Fig. 2. The model had an overall height of 14.2 cm, an overall width of 12.2 cm, and a depth of 21.8 cm. With the apertures blanked off, a resonant frequency of 768 MHz was measured. A resonant frequency of 762 MHz was calculated for the lowest order eigenmode using the 3-D calculation, in close agreement with the measurement.

Plotted in Fig. 5 are the direction (5a) and magnitude (5b) of the wave magnetic field at the mouth of the scale-model folded waveguide resonant cavity. Measurements were taken with a small loop probe inserted through holes in the walls of the cavity. The direction of the field reverses in adjacent sections of the structure in agreement with predictions (see Fig. 4). The magnitude of the field along a path through the folds has a sinusoidal dependence roughly analogous to the structure of the TE₀₁ mode in an

Fig. 5. Measured wave magnetic field at the end of a four-section coupler similar to that displayed in Fig. 2 having overall dimensions 14.2 cm high, 12.2 cm wide, and 21.8 cm deep. Measured field direction is shown in (a), and measured field amplitude around the folds is shown in (b).

equivalent unfolded rectangular waveguide. Fields at the back of the coupler are equal in magnitude to the fields at the front of the coupler, characteristic of a mode above cutoff rather than an evanescent mode.

Good agreement between calculational results and the experimental measurements displayed in Fig. 5 has been obtained. Figure 6 shows the calculated direction (6a) and magnitude (6b) of the

Fig. 6. Calculated wave magnetic field at the end of a four-section coupler similar to that displayed in Fig. 2 having the same overall dimensions as described for Fig. 5. Calculated field vectors are shown in (a). Calculated field amplitude along the same path in which measurements in 5(b) were taken is shown in (b).

wave magnetic field around the folds of the waveguide, analogous to the bench-top measurements displayed in Fig. 5. Dimensions used in the calculation are the same as those of the hardware model described earlier in this section. The calculated features of the field are seen to be nearly identical to the measured features.

Shown in Fig. 7 are the direction (7a) and magnitude (7b) of the wave magnetic field at the

Fig. 7. Measured wave magnetic field at the end of a tapered folded waveguide coupler similar to that displayed in Fig. 3. The overall dimensions are the same as those described in Fig. 5. Measured field direction is shown in (a), and measured field amplitude around the structure is shown in (b).

mouth of a tapered folded waveguide similar to the waveguide illustrated in Fig. 3. The overall dimensions are the same as those of the simple folded waveguide model described at the beginning of this section. It also has four sections as did the earlier model. Once again the fields reverse in adjacent sections. The magnetic field amplitude concentrates in the narrow height sections at the mouth of the structure. An overall reduction of amplitude within the large apertures at the mouth of the coupler is found when compared with the nontapered folded waveguide (Fig. 5b). Figure 8

Fig. 8. Measured wave magnetic field amplitude versus path length around the tapered folded waveguide at the back wall of the coupler.

shows the amplitude distribution at the back of the tapered folded waveguide. The fields are more nearly symmetric here because the back half of the tapered folded waveguide has the form of a nontapered folded waveguide (this simplifies impedance adjustment of the coax input). Comparing Fig. 8 to Fig. 7b, it is observed that the fields at the back of the guide have roughly comparable amplitude to fields at the end of the taper at the coupler mouth when an average of the distributions is taken. This indicates that the fields are predominantly propagating rather than evanescent. The lower amplitude of fields relative to those of the untapered waveguide indicates that the quality factor, Q , for the tapered guide is lower than that for the untapered case. This has been verified from separate Q measurements of the two couplers. The lower Q is a result of the lower ratio of volume to surface area for the tapered guide and the excitation of lossy higher order modes in transition regions within the coupler. The loaded Q when plasma is present is expected to be much lower than the unloaded Q even for the tapered guide so that coupling efficiency is expected to be high in any case.¹⁴

After an examination of some of the basic experimental and theoretical properties of folded waveguides is complete, full-scale tests of a high-power version of the folded waveguide coupler will be performed on the Radio Frequency Test Facility (RFTF) at the Oak Ridge National Laboratory.¹⁷ These tests will provide some experimental information on folded waveguide coupling to a magnetized plasma.

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