TESTS OF A HIGH-POWER FOLDED WAVEGUIDE COUPLER FOR ICRF HEATING*

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ABSTRACT

A full-scale folded waveguide coupler has been fabricated which will provide information on power handling, impedance matching, and multipactor effects. The coupler dimensions are $30 \times 60 \times 300$ cm. The cross section of the coupler is small enough that a phased pair of couplers could be placed in a single Tore Supra or TFTR port. A single coupler could be placed in a CIT-size port. A movable back plate allows frequency adjustment over the range 78–140 MHz. Impedance matching at the waveguide has been achieved using a movable coaxial transmission line feed. Bench-top comparisons with loop antennas have been made. The folded waveguide coupler will be mounted on the Radio Frequency Test Facility for high-power tests up to 1.5 MW.

INTRODUCTION

A general description of the folded waveguide coupler concept and a simplified theoretical analysis are presented in Ref. 1. Early experimental tests on a small-scale folded waveguide and comparisons with a more elaborate 3-D finite difference calculation of coupler fields are discussed in Ref. 2. This paper describes a high-power, full-scale coupler, which will be tested at 80 MHz on the Radio Frequency Test Facility (RFTF) at the Oak Ridge National Laboratory.

High-power tests will be performed at 80 MHz primarily because RFTF has ample power (~ 1.5 MW) available at this frequency. At 80 MHz, the coupler length is approximately 3 m. At 120 MHz where Tore Supra waveguide experiments would operate, the coupler length is reduced to 1.4 m. Although reasonably good performance is expected for the 80-MHz test waveguide, much better performance has been calculated for a 120-MHz coupler (Ref. 1).

Low-power bench-top measurements have been made on the 80-MHz test waveguide, and these have been compared directly with measurements on a loop antenna tuned to 65 MHz. Power handling and

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coupling efficiency in the presence of plasma can be roughly estimated for the folded waveguide based on this loop/waveguide comparison and on knowledge of loop performance gained through experiments. Power handling and coupling efficiency estimates will be compared to calculations.

RESULTS

Figure 1 shows the poloidal distribution of folded waveguide, toroidal wave magnetic fields taken along the vertical midplane of the coupler. The poloidal distribution is reasonably smooth at a distance of 10 cm in front of the coupler. Little excitation of high-order poloidal modes is expected for this spatial distribution. Somewhat greater excitation of high-order modes occurs closer to the coupler (Fig. 1b), but most of the power is still in the lowest-order modes.

A plot of the radial decay of the toroidal wave magnetic field away from the coupler is shown in Fig. 2a. Figure 2b shows the radial decay of the toroidal wave magnetic field for a 65-MHz loop antenna having the same cross-sectional dimensions as the folded waveguide coupler. The comparison shows almost the same decay length for loop and waveguide fields. Other measurements have shown that the directions of the wave magnetic field vectors for loop and waveguide couplers are nearly the same in front of the couplers. The addition of a Faraday shield in the folded waveguide apertures does not change the field patterns but only lowers the unloaded quality factor of the waveguide about 15%.

Peak electric field for the folded waveguide coupler can be related roughly to the peak electric field between a loop antenna and its Faraday shield through the relation,

$$\frac{E_w^2}{E_\ell^2} = \left(\frac{16d^2}{\omega_0 \epsilon_0 V \omega L} \right) \left(\frac{f}{g} \right)^2 \frac{Q_w}{Q_\ell} h^2, \quad (1)$$

where d is the distance between the loop and Faraday shield, L is the loop inductance, V is the waveguide volume, Q_ℓ , Q_w are unloaded quality factors, ω_0 and ω are waveguide and loop frequencies, f and g are field enhancement factors due to surface shapes, and h is the unloaded average wave magnetic field amplitude of the loop coupler at its load surface divided by the unloaded average wave magnetic field of the folded waveguide coupler at the same load surface. In Eq. (1), electric fields are calculated for equal power coupled to the load surface by loop and waveguide couplers. The loop antenna is assumed to have a voltage minimum at its center. The loop antenna used in the experimental comparison has a Faraday shield 1.5 cm from the current strap. The shield consists of a single row of round tubes, 1.2 cm in diameter, that yields a field enhancement factor of 1.45. From measurements of waveguide and loop coupling efficiencies to a resistive surface, the quantity, h , can be inferred using Eq. (2). It is found to be ~ 1.8 for resistive surfaces placed between one and ten centimeters from the couplers. For the test folded waveguide, a field enhancement factor of 2.6

is calculated. Other measured quantities are: $\omega_0 = 2\pi \times 80$ MHz, $\omega = 2\pi \times 65$ MHz, $V = 0.468$ m³, $L = 2 \times 10^{-7}$ H, $Q_w = 2544$, and $Q_\ell = 590$. Using these values, $E_w/E_\ell \approx 1$.

Note that the preceeding comparison is for a specific loop coupler and a specific folded waveguide coupler. Reductions in electric field for the folded waveguide coupler occur at higher frequencies and for increased vane tip radii. Table I shows the calculated improvements over the test waveguide as operating frequency and waveguide size are increased. Relative vane spacing can also be increased near the center of the coupler, where most of the Poynting flux occurs, to reduce field levels. Somewhat fewer options are available for reducing fields for the loop coupler used in this comparison. In addition, fields for the loop coupler may be considerably higher in the components that attach to the antenna (e.g., radial feed lines, feedthroughs, supports, tuning elements, etc.). Fields for the folded waveguide coupler described in the preceeding comparison are already the largest fields anywhere in the system. Finally, the position of maximum field for the folded waveguide coupler is 1.5 m back from the mouth of the coupler, well away from the plasma surface. For the loop coupler, high electric fields exist very close to the plasma surface. Tests with plasma on RFTF may provide information on the importance of this and other differences between loop and folded waveguide couplers. Another unknown is the effect of multipactor within the waveguide. Techniques to suppress multipactor may be required to maximize power handling of the folded waveguide.

Folded waveguide coupling efficiency, η_w , can be related to loop coupling efficiency, η_ℓ , by the following relation:

$$\eta_w \approx \frac{1}{1 + h^2 \left(\frac{1}{\eta_\ell} - 1 \right)} \quad (2)$$

As discussed earlier, $h \approx 1.8$ so that, for a common loop coupling efficiency of 90% in the presence of plasma, the test waveguide coupler would have an efficiency of approximately 74%. The calculated efficiency for the test waveguide is 68%, as shown in Table I. This rough agreement between theory and measurement provides some degree of confidence in the calculated high efficiencies (94-99%) and low electric fields at 120 MHz (Table I).

REFERENCES

- 1T. L. Owens, "A Folded Waveguide Coupler for Plasma Heating in the Ion Cyclotron Range of Frequencies," IEEE Trans. Plasma Sci., PS-14 (6): 934-46 (December 1986).
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Table I

Comparison of a pair of 80 MHz test couplers to a single 4 section coupler and a pair of 8 section couplers designed for 120 MHz operation in a single Tore Supra port (60×70 cm). Total power is 4 MW with a 10 cm plasma/coupler separation.

	4-section coupler	8-section coupler pair	10-section test coupler pair
Electric field in coupling apertures (kV/cm)	1.45	1.75	1.62
Peak electric field (kV/cm)	12.65	25.6	49.3
Plasma loaded quality factor	213	834	2609
Unloaded quality factor	23,440	13,171	5500
Coupling efficiency (%)	99	94	68

Fig. 1. Poloidal distribution of the toroidal wave magnetic field along the folded waveguide coupler midplane. Curve (a) is taken 10 cm in front of the coupler face, and curve (b) is taken 1.2 cm in front of the coupler face.

Fig. 2. Radial decay of the toroidal wave magnetic field along a chord at the center of the couplers. Curve (a) is for the test folded waveguide coupler, and curve (b) is for the loop coupler for equal input power level.

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