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Phased Waveguide Array with Fixed Tuning Elements

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ABSTRACT

The waveguide grill excites both penetrating lower hybrid waves and surface plasma waves. Quarter wavelength tuning elements attached to the sides of a twin waveguide are shown to reduce the surface wave component by a factor of ~ 3 .

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I. Introduction

The phased waveguide array^{1,2} promises to be the most practical means for launching high power lower hybrid waves into toroidal plasmas. These devices consist of a series of waveguides placed side-by-side along the field lines. Each element is excited at the same frequency ω in the fundamental TE_{10} mode. If the separation between the guides is less than $\lambda_0/2$, then it is possible to excite slow waves by appropriate phasing of the individual elements.

Extensive tests have been carried out with multiple arrays³⁻⁷ in which each element was driven at approximately the same power level, but shifted in phase from its neighbors by $90-270^\circ$. Each of these arrays coupled satisfactorily to plasma waves—the reflection coefficient was typically 10-15%. However, the distribution of power between penetrating electrostatic lower hybrid waves and electromagnetic surface waves has not yet been determined experimentally.

It is important to minimize the surface wave component of the radiated power; surface waves give rise to undesirable nonlinear interactions⁸⁻¹² as well as to lowered heating efficiency. Two independent strategies have been devised to cope with this problem: (1) Theoretical analysis has shown that the surface wave radiated by a grill can be minimized by employing multiple waveguide arrays (> 2 elements) and by driving the outside guides at reduced power.¹³ (2) The

Leningrad group has pointed out that an inductive comb structure will convert surface waves to plasma waves.^{14,15}

The twin waveguide couples very efficiently to plasma waves, but it also generates a strong surface (fast wave) component. Linear coupling theory² predicts significant reduction of the surface component on placing additional waveguide elements on each side of the twin array. The elements can either be active or passive; the passive elements in turn can either be absorbing or reflecting. In this paper we compare the wave fields excited in a plasma by a twin guide and by a modified twin guide, in which fixed tuning elements are attached to the sides of the twin guide like outriggers from a canoe. The tuning elements reduce the surface wave because they force the applied electric field E_z to be (periodically) zero at the end of each conducting septum. Alternatively, one can consider the tuning elements to be a practical, compact realization of the comb structure, in which the individual units are positioned to enhance the excitation of slow waves.

This development is also the outgrowth of recent work on a two-element grill driven by a single guide, in which the power coupled into the idle guide was reflected back into the plasma.¹⁶ It was suggested then that an equivalent result could be achieved by attaching fixed tuning elements to the sides of an active guide or guides, and that the

tuners would simultaneously simplify the engineering requirements for multiple arrays and reduce the magnitude of the surface waves excited by the grill. In this paper we report results demonstrating that tuners can reduce the surface component of a twin grill by a factor of ~ 3 .

II. Design Considerations

The twin, phased waveguide has been used to launch lower hybrid waves for a variety of purposes in linear^{3,4,17} and toroidal⁷ plasmas. It couples efficiently to slow plasma waves and is uncomplicated and inexpensive to design and construct. Yet the twin guide is certainly not an ideal slow wave generator. It launches an extremely broad spectrum of plasma waves, as shown by a numerical calculation of the boundary value problem² given in Fig. 1 ($n_{\parallel} = \lambda_0/\lambda_{\parallel}$ is the normalized wavenumber parallel to the magnetic field).

The power spectrum, unfortunately, contains a resonance near $n_{\parallel} \sim 1$. In this spectral interval the power is indeed radiated past the mouth of the grill, but does not in general penetrate the surface layers of the plasma column, and therefore appears as a surface wave. Only waves which satisfy the accessibility criterion,¹⁸

$$n_{\parallel}^* > \left(\frac{n}{n_c} - 1\right)^{1/2} \frac{\omega}{\omega_c} \left[1 + (1 + \omega_c^2/\omega^2 (n/n_c - 1))^{1/2}\right], \quad (1)$$

can penetrate to a density n , where ω_p and ω_c are the electron plasma and cyclotron frequencies and $n_c = m_e \omega^2 / 4\pi e^2$. For the conditions of our experiment ($B = 13$ kG, $n \sim 1.5 \times 10^{12} \text{ cm}^{-3}$) $n_{\perp}^* = 1.4$. About 1/4 of the radiated power will appear as a surface wave ($n_{\perp} < 1.4$).¹⁹

To illustrate the distinction between surface and body waves, we have calculated the ray trajectories of selected waves emanating from a point source into a density ramp. The calculation makes use of the eikonal method described by Stix,²⁰ and takes account of the electromagnetic as well as the electrostatic terms in the dispersion relation. If one writes the dispersion relation as

$$D(\omega, \bar{k}, \bar{r}) = a n_{\perp}^4 + b n_{\perp}^2 + c = 0 \quad (2)$$

where $n_{\perp}$ is the index of refraction perpendicular to the magnetic field and a , b , and c depend on the plasma density and magnetic field,²⁰ the ray trajectory is defined by the equations

$$\begin{aligned} d\bar{k}/dt &= \partial D / \partial \bar{r} / \partial D / \partial \omega \\ d\bar{r}/dt &= \partial D / \partial \bar{k} / \partial D / \partial \omega . \end{aligned} \quad (3)$$

From the ray trajectories plotted in Fig. 2 one can see that short wavelength waves penetrate the surface layers and cross the plasma column at an angle $\theta \sim (\omega/\omega_p) \sim 12^\circ$.²¹ Medium wavelength waves for which $n_{\perp} \sim n_{\perp}^*$ propagate at angles less than θ . Long wavelength waves for which $n_{\perp} < n_{\perp}^*$ pene-

trate only partially into the surface layers, convert to fast waves, deflect out of the column and become trapped on the surface.¹⁹

The distribution of power can be improved by increasing the number of active elements in the array. An alternative method of reducing the width of the spectrum is to add fixed sections of shorted waveguide, or tuners, to each side of the phased array, as illustrated in Fig. 3. The design of this system is dictated by whether the grill is to be driven in a balanced or unbalanced configuration (180° or 90°). The former is appropriate for pure plasma heating applications; the latter would be more appropriate for driving steady-state currents within a toroidal plasma. If balanced operation is desired, as in our test, then each element should be separated along the field lines from its neighbors by $\sim \lambda_0/2n_u$. The depth of the shorted guides is determined by the need to return the power back into the plasma column with the electric field shifted in phase 180° from that in the adjacent guides. For this purpose one should design the tuner depth to be (approximately) $\lambda_g/4 = \lambda_0/4(1 - \epsilon_0^2/4\epsilon^2)^{1/2}$, where a is the long dimension of the guide.

In this paper we compare the performance of a simple twin array with a six-array formed by adding two fixed, shorted waveguide elements on each side of the two active guides. Characteristics of both systems can be calculated from the solution of the boundary problem given by Brambilla.² The twin guide requires only a straightforward application

of the theory. The 6-element active-passive system can be solved either by changing the boundary conditions along the grill, or by applying the theory in its present form. In the latter course one first estimates the power coupled into the passive guides and inserts this power (at 180°) into the computer code. This procedure is repeated 3 or 4 times until the input and output powers match in each of the passive guides.

The effect of the tuning elements on the spectrum is illustrated in Fig. 1. The spectrum is much better defined; a significant fraction of power at long wavelengths is transferred into the shortwave portion of the spectrum near $n_{\parallel} = 2.8$. This transfer takes place because the slow waves ($n_{\parallel} \sim 2.8$) can satisfy the boundary condition that E_z must be zero on the ledge terminating each metallic septum, but the fast waves ($n_{\parallel} \sim 1$) cannot. For comparison we also show in dotted lines the spectrum obtained if the power in the idle guides is absorbed rather than reflected. Even in this case the periodic boundary conditions considerably reduce the long wavelength component of the spectrum. The reflecting array is, of course, considerably more efficient, since it avoids power wastage in the idle guides.

The calculated reflectivity for our conditions ($V_n = 0.5 \sim 1 \times 10^{12} \text{ cm}^{-4}$) is 4% for the twin guide and 9% for the 6-array. We note that increased reflectivity is

the penalty one must pay for the improved spectrum. Power shifted to shorter wavelengths does not couple as efficiently to plasma waves. The circulating power in the (near) idle guides is 8% of the power in the active guides; the circulating power in the two outer tuners is only 0.5%. Obviously, the two outer guides are redundant for 180° excitation. (This observation does not apply to 90° excitation.)

The computer code also yields the phase angle of the power cross-coupled from the active guides. For our conditions the phase angle of the dominant TE_{10} reflected mode (at the near passive guides) should be $203-207^\circ$. For optimum tuning then, the passive elements should be $63-67^\circ$ in depth, rather than the nominal 90° .

III. Results

Tests of the two antennae were conducted on the linear H-1 plasma source,²² which provides a 2 m long, 10 cm diam. plasma column of moderate density ($1 - 2 \times 10^{12} \text{ cm}^{-3}$) immersed in a 13 kG magnetic field. A twin, teflon-loaded waveguide was placed in the surface layers of the plasma,¹⁷ midway between the ends of the column, as shown in Fig. 4. We report results from a simple twin guide and a twin guide modified by the addition of two elements on each side. The tuning elements were 70° in depth, provided the dielectric constant of the teflon was 2.3. The modified grill was much too large

to be inserted directly through the port. It was necessary to press the tuners into position by reaching through a port on the opposite side of the vacuum vessel. The two center guides were driven at ~ 100 W (no nonlinear effects) by power from a 2.45 GHz magnetron, as shown in Fig. 4.

Externally, we monitored the incident and reflected power in the active guides by means of directional couplers. Internally, we measured the radial profiles of both density and rf fields with a well-shielded triaxial "T" probe capable of axial motion.

Reflection as a function of phasing in the two active guides is shown in Fig. 5. With only two elements in place, the reflectivity varies from ~ 8 to 35% as the phase varies from 180° to 0° , as shown earlier. The addition of the tuning elements strongly reduces the sensitivity to phase--the reflection varies only between 15 and 22%. Qualitatively, one can understand the reduced reflection at 0° by realizing that the tuning elements prevent the excitation of pure surface waves ($n_{\parallel} \sim 1$). For 180° excitation the theory predicts 8-9% reflection, so that the system requires further tuning if one desires optimum coupling.

The most significant comparison of the two exciters is shown in Fig. 6 in the form of radial scans of the rf field intensities at three different positions along the plasma column. Both arrays excite broad resonance cones of

comparable magnitude, in which the leading edge of the cone is directed at an angle of $\sim 12^\circ$ with respect to the magnetic field. The most striking difference between the two is a reduction in the width of the resonance cone and in the amplitude of the surface wave component by a factor of ~ 3 when the tuners are added. This reduction is not quite as large as one would expect from the spectra illustrated in Fig. 1, in which a reduction of ~ 6 would be expected for $n_{\parallel}^* \sim 1.4$.

These data, then, provide experimental confirmation for what has been an article of faith in lower hybrid heating--namely, that strong reduction of surface wave excitation is possible with multi-element arrays.

IV. Discussion

It is possible to drive a phased array with a single waveguide as well as with a twin guide. Such a design requires only one standard waveguide and one commercial ceramic vacuum window, and therefore permits considerable reduction in system complexity and cost, compared with a multi-element, purely active array. In addition, the passive elements reduce the surface wave component of the wave launcher. At present such systems may find application in lower hybrid heating of ultra-compact tokamaks, where problems of access limit the size of an array. In the future these

systems may be more generally useful to rf designers, when both the characteristics of the plasma to be heated and the nonlinear performance characteristics of the rf antenna are well understood.

Mechanically tuned arrays do possess certain disadvantages, however. There is a loss of flexibility, in that the tuning is fixed. In principle one could change the tuning mechanically, but in practice the presence of mechanical control elements would be highly undesirable in a toroidal reactor. The addition of passive elements also imposes more stringent requirements on the power handling capacity of the active guides. In fact the nonlinear behavior of both the active and the active-passive waveguide array is still an open question.

Perhaps the most practical application of tuned elements will be in hybrid systems — arrays consisting mostly of active elements, but with several passive elements added on each side. The hybrid would reduce the surface wave component and at the same time minimize the disturbance to the blanket which must surround a D-T reactor. It should be understood that the reduction of surface wave will depend on the number of elements and will not be as dramatic as in the 2-element array. We calculate, for example, that adding 2 outside passive elements to a 4-array (same characteristics as in Fig. 3) would effect a 40% reduction in surface wave.

One final, more speculative application of tuned elements in lower hybrid heating of tokamak plasmas is worthy of comment. In a number of important rf heating experiments, both in operation^{6,7} and planned, the vacuum wall is not smooth, but consists mainly of stainless steel bellows. Lower hybrid waves passing through the plasma column or scattered out of the column by drift waves, and surface waves emitted by the waveguide grill, strike the undulating surface of the bellows and are reemitted as slow waves—but with a spectrum determined by the bellows and the surface plasma rather than by the original radiator.

It may well prove desirable to design the vacuum bellows such that the periodicity is $\lambda_0/4$, as in Fig. 7, where $n_{\parallel 0}$ is the desired wavenumber. In this way one will ensure that the principal component of the reemitted waves will be $\sim n_{\parallel 0}$. Before one embarks on such a radical redesign of vacuum enclosures, however, it would be prudent to calculate whether multiple reflections from the undulating wall would drive up the $2 n_{\parallel 0}$ and $3 n_{\parallel 0}$ components of the spectrum, leading to undesirable surface heating.

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Fig. 1. Power spectra excited by a twin waveguide, a twin guide with four reflecting tuners (180° phase shift), and a twin guide with four absorbing tuners. The guide and tuners are loaded with teflon ($\epsilon = 2.3$) to depress the cut-off frequency well below the signal frequency, $f = 2.45$ GHz. $\omega n = 10^{12} \text{cm}^{-4}$; periodicity = 2.0 cm.

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Fig. 2. Ray trajectories calculated for 2.45 GHz lower hybrid waves of varying wavenumber $n_{\parallel}$ propagating across a density ramp and plateau ($n = 2 \times 10^{12} \text{ cm}^{-3}$). Waves for which $n_{\parallel} < 1.4$ give rise only to surface modes.

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Fig. 3. Twin guide and twin guide with four tuning elements. The periodicity is 2 cm; the (inner) dimension of the active guide is 1.8 cm and for the passive guides, 1.3 cm. The height of the guides is 5.8 cm. Arrows indicate the direction of power flow.

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Fig. 4. Experimental test arrangement.

Fig. 5. Reflection as a function of phase angle in the active waveguides for (a) twin guide and (b) twin guide with tuning elements ($n = 7 \times 10^{11} \text{ cm}^{-4}$).

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Fig. 6. Radial variation of rf field intensity 3, 8, and 11 cm from the (axial) center of the waveguide. At $z = 3$ cm the probe is 1 cm past the twin guide but within the first tuning element of the 6-array. The plateau density n_e is $1.5 - 2 \times 10^{12} \text{ cm}^{-3}$.

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Fig. 7. Resonant bellows for tokamak plasma heated by lower hybrid waves.

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