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TRAVELING WAVE RESONANT ANTENNAS  
FOR FAST WAVE HEATING SYSTEMS**

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# Advantages of Traveling Wave Resonant Antennas for Fast Wave Heating Systems

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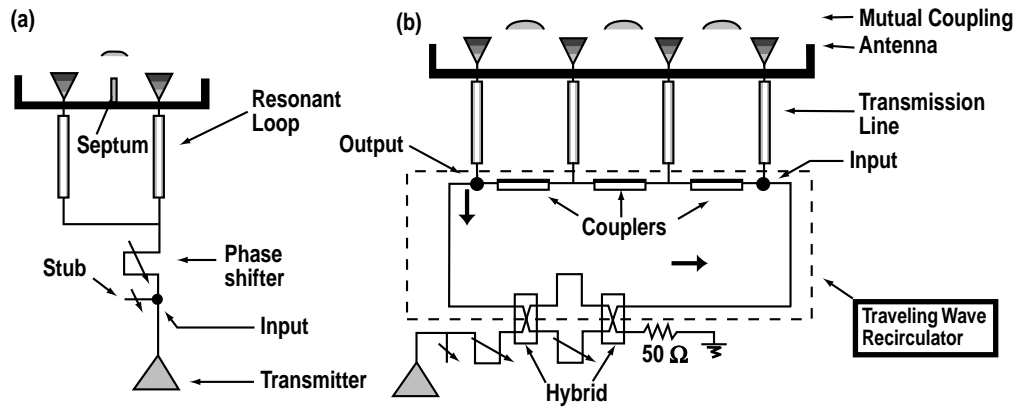
**Abstract.** The resilience of a maximally flat externally coupled traveling wave antenna (TWA) is contrasted with the sensitivity of a simple directly driven resonant loop array to vacuum and plasma conditions in DIII-D. We find a unique synergy between standing and traveling wave resonant TWA components. This synergy extends TWA operation to several passbands between 60 and 120 MHz, provides 60°–120° tunability between elements within a 1–2 MHz bandwidth and permits efficient and continuous operation during ELMing H-mode.

A relatively new and rapidly evolving technology based on Traveling Wave Antennas (TWAs) and associated standing and traveling wave resonant components [1–7] is analyzed using computer simulations based on a coupled lossy transmission line theory described elsewhere [8]. The simplified engineering characteristics of this technology combined with a remarkable insensitivity to changing plasma conditions to offer an excellent solution, over the ion cyclotron range of frequencies, to the plasma heating, current drive, and profile control requirements of tokamak experiments.

A loop coupled two-element rf circuit similar to that used on DIII-D is sketched in Fig. 1(a). This circuit, when analyzed using the DIII-D antenna modeling parameters [8] shown in Table 1, shows a high level of sensitivity to plasma loading as shown in Fig. 2(a). Note that the reflection coefficient ( $S_{11}$ -parameter) minimum is matched only to H-mode. This minimum in the reflection coefficient and the bandwidth change with variations in reactive and resistive loading, respectively. This sensitivity is greater than, but consistent with, previous observations during ELMing H-mode using the loop coupled antenna systems now on DIII-D [9].

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**FIGURE 1.** (a) Simplest resonant loop antenna; (b) maximally flat TWA.

A flat externally connected TWA alternative [4] is sketched in Fig. 1(b). We are exploring the advantages of mixing standing and traveling wave resonant components in this approach to produce a more user friendly and experimentally flexible antenna system. For example, the length of standing wave resonant line between each antenna element and the connection to an external coaxial coupling network can be increased to (1) locate all tuners outside the DIII–D concrete wall, (2) access enough TWA passband harmonics to effectively cover a 60–120 MHz operating range, (3) achieve 60°–120° phase tunability within each passband by changing frequency within a 1–2 MHz bandwidth and (4) maintain the same plasma coupling efficiency, regardless of line length (apart from the added ohmic loss). Without spoiling these features, we add a traveling wave resonant loop, or recirculator [1,2,4–7] as sketched in Fig. 1(b).

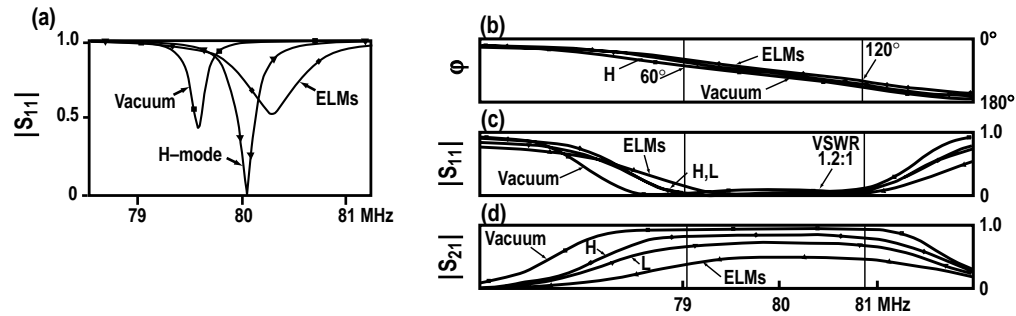
The narrow passband features are shown in Fig. 2(b–d). Figure 2(b) predicts the variation in phase between elements from 60° to 120° for H–mode loading in DIII–D. The  $\pm 40^\circ$  phase shift for vacuum and ELM loading will be discussed later.

With the transmitter protection stub in its neutral position (*i.e.*, no tuning), Fig. 2(c) predicts that the reflected power from the TWA is less than 1% between 60° and 120° — except for an increase to about 4% (1:4:1 VSWR) during ELMs and near 60°. The impact of this increase on multi-pass TWA operation is discussed later.

The uncoupled power at the TWA output during single pass operation  $|S_{12}|^2$  is predicted in Fig. 2(d). Note that the uncoupled power decreases with increasing plasma load resistance. The level during H–mode is near 75%, whereas that during

**TABLE 1.** Plasma facing element modeling parameters

Load	$\rho(\Omega/m)$	$\Delta L/L_v$	$\Delta M/M_v$
Vacuum (eff.)	1.7	0 %	0 %
H–mode	6.5	–11	–35
L–mode	11	–16	–50
ELMs	26	–25	–72



**FIGURE 2.** (a) Reflection from resonant loop antenna; TWA phase (b), reflection (c), and transmission (d) S-parameters.

L-mode is near 50%. Allowing for the  $<1\%$  reflected power shown in Fig. 2(c), we predict for a single pass through the TWA that the power absorption efficiencies ( $\eta_{sp} = 1 - |S_{12}|^2$ ) are 25% for H-mode and 50% for L-mode.

The recirculator circuit in Fig. 1(b) recovers the uncoupled power and returns it to the TWA input in-phase with the transmitter, the traveling wave resonant circulating power increases until the transmitter power is effectively coupled to the TWA. More detailed modeling of a recirculator with a variable coupling factor is given elsewhere [1,2,6].

The variation of multi-pass coupling efficiency ( $\eta_{mp}$ ) as functions of  $\eta_{sp}$ , TWA input VSWR, and input-output phase shift is shown in Fig. 3. Note that  $\eta_{sp}$  is optimum for L-mode in Fig. 3(a) and H-mode in Fig. 3(b).

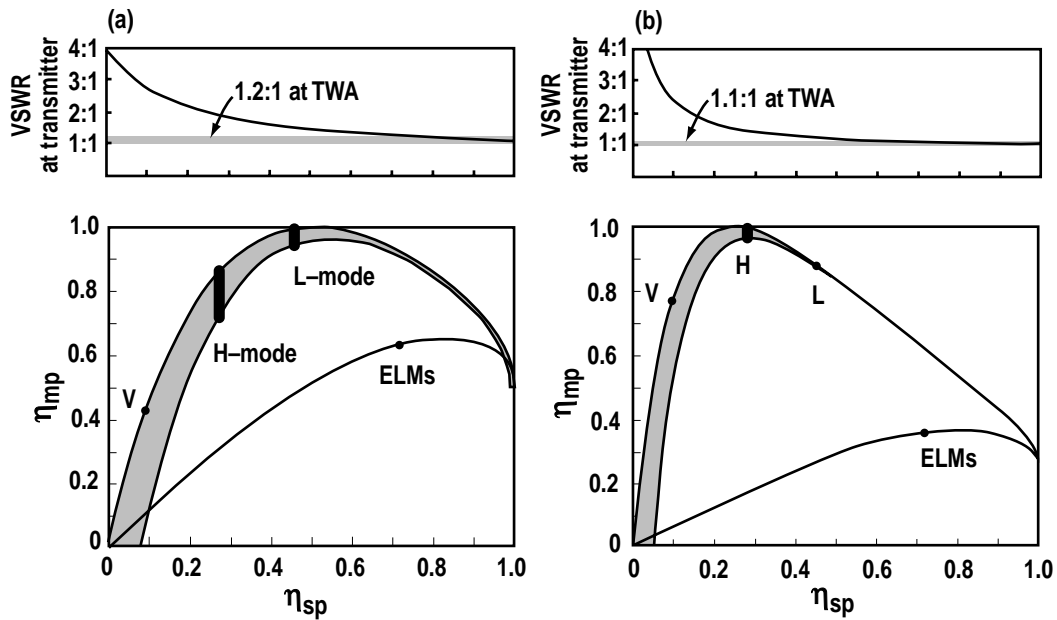
Note that an increase in TWA input VSWR to 1.4:1 occurs near  $60^\circ$  in Fig. 2(c). This is permissible because the transmitter VSWR does not increase appreciably due to the strong loading during ELMs. Thus multi-pass operation during ELMing H-mode is possible without an automated matching system.

The phase shift during ELMs mistunes the recirculator traveling wave resonance [6] and  $\eta_{mp}$  is reduced to about 60% in Fig. 3(a) and 40% in Fig. 3(b). This loss in efficiency during ELMs must be weighed against the benefits of reduced rf voltage and elimination of transmitter tripping and arc inducing problems during ELMs. Continuous operation during ELMing H-mode is maintained because the lost power is diverted to the dummy load and not toward the transmitter.

Vacuum conditioning between shots can be performed by tuning the transmitter stub for near 1:1 VSWR and the recirculator phase shifter for an integral number of wavelengths. During plasma operation the transmitter stub is returned to its neutral position. Notably, the transmitter trips only during arcs, as desired for reliable vacuum conditioning and plasma operation.

In conclusion, we have shown that a directly driven antenna can experience drastic increases in reflected power during worst case changes in plasma conditions. For the same conditions, the resilience of a TWA has been demonstrated.

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**FIGURE 3.** Efficiency and VSWR predictions for a recirculator with (a) 50% coupling, and (b) 25% coupling.

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