CONVERSION OF THE FOUR-STRAP ARRAY IN DIII-D TO A TUNABLE TRAVELING WAVE ANTENNA

by

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ABSTRACT

The *in situ* conversion of the two-standing wave resonator driven four-strap array in DIII-D to a new type of traveling wave antenna (TWA) is introduced. First observations are reported on (1) broad frequency range tunability; (2) narrow frequency band phase control; (3) single pass transmission loss and modification caused by resistive and reactive sheet simulators of plasma loading; and (4) recirculating power resonance and gain in a traveling wave resonator (TWR) driven TWA.

1. INTRODUCTION

To maximize fast wave current drive (FWCD) in the ion cyclotron range of frequencies (ICRF), the rf radiation spectrum must track an optimum phase velocity¹ that increases with electron heating² and changes with L-H and other mode transitions, or ELMs. Broadband frequency and phase tunability is needed to access the desired FWCD, electron heating, and ion cyclotron resonance heating scenarios. A transmitter/tuner/antenna system that meets these needs, but also switches rapidly between scenarios, is the ICRF enabling technology challenge for the future.

The combline TWA³⁻⁷ exhibits phase control between $(0, \pi)$ within a preselected cutoff frequency passband, and thereby suits its principal mission — FWCD at the highest frequency commensurate with transmitter power, FWCD efficiency, and avoidance of ion cyclotron resonance. In-band rapid switching between electron heating during startup, and FWCD during L and H-mode, is another accessible scenario.⁸ To access ion heating scenarios, however, requires an in-vacuum tunable capacitive load, a change in the tune during a vent, or sets of combines tuned to preselected frequencies.⁸ This latter solution is viable for next generation tokamaks, such as ITER⁴ and Ignitor.^{5,6} Issues for TWAs in general are the lack of physics and technology validation at high rf power, and/or with plasma loading, sheath rectification and impurity generation.⁹ To perform near term research on as-built antennas, including broad phase and frequency tunability, consider the externally tuned TWA⁶ described herein.

2. THE EXTERNALLY TUNED TWR DRIVEN TWA

The TWR driven TWA circuit in Fig. 1 utilizes an as-built boxed-in four-strap array with septa and Faraday shield, such as the DIII-D four-strap array mock-up at ORNL (the Mock-up), or the B4C shielded four-strap array now in DIII-D (B4C Prototype). Each strap is made into a transmission line cavity, and tuned for standing wave resonance between the strap-short and an external coax-short using a line stretcher (or tuning capacitor).^{6,10} Power is critically coupled into or out of just the end strap-cavities. Interior strap-cavities are powered only by mutual coupling. Power not radiated or absorbed in the walls is recirculated in a TWR, using a 3 dB hybrid.

Parameters based on a resolution of theory with experiment are given in Table I. Note that (1) $Z_0 = 42/93 \Omega$ implies with/without a Faraday shield (for example); (2) k_{mn} are the TWA coupling factors; (3) $k_{m,m\pm1} = 39\%$ without septa (as preferred); and (4) $R_p = k_{23}X_L \gtrsim 3 \Omega$ is the critical load resistance (where $kQ = 1$). Notably, L and H-mode loads in DIII-D^{11,12} are less than this R_p as desired.

Recently, toroidal wave number (k_{tor}) spectra for a 1 m TWA were simulated. Remarkably, nearly 100% of the power can be absorbed by the plasma without significant change in the k_{tor} spectrum relative to no absorption, except well above the optimum k_{tor} for FWCD. Since higher k_{tor} are more evanescent,¹¹⁻¹³ there will be much less change in the launched fast wave spectrum.

3. EXPERIMENTAL RESULTS

Single-pass observations of the S -parameters at TWA ports P1 and P2 were made without the TWR in Fig. 1. The magnitude and phase of reflection (S_{11}, S_{22}) and transmission (S_{21}, S_{12}) parameters were measured. Transmission reciprocity was observed. The observed 2 MHz passband was predicted by theory,³ using the parameters in Table I. The observed smooth phase variation, about $\pi/2$ at midband, is consistent with a theory for unidirectional traveling wave (versus a standing wave). By lengthening the strap-cavities, the passband was down-shifted from about 61 to 63 MHz to about 48 to 50 MHz, as predicted.³ Following this procedure, wider band tuning (e.g., 30 to 120 MHz) can be achieved.

Frequency responses for the Mock-up are displayed in Fig. 2. Filter-like passbands are predicted by applying combline theory³ to a TWA with half-wave resonant strap-cavities.⁶ There are no spurious passbands below the first upper filter passband at about 140 MHz, as expected.³ The highest transmission efficiency occurred for no loading, and is less than unity due to $\sim 10\%$ reflection from P1 and P2, wall absorption, and/or free space radiation. Tuners were not used to reduce these reflections, in order to study TWA passband responses. The family of passband profiles in Fig. 2 are parametric in (a) resistive (carbon filled plastic), or (b) reactive (aluminum) sheet dummy loads of larger area than the Faraday shield. The load was changed by changing the shield-sheet gap. The observed passband attenuation and slight down-shift in Fig. 2(a) compares with expectation for a RLC resonant circuit.⁶ As a potential calibration technique, each external short was replaced by a 2.7 ohm resistor load. The observed attenuation was slightly greater than that for the 1.5 cm gap. This suggests that plasma relevant 1 to 3 Ω /strap loads^{11,12} can be achieved with plasma relevant 2 to 8 cm shield-sheet gaps. A family of profiles for shield-metal sheet spacings are shown in Fig. 2(b). The slight increase in frequency with smaller gaps is consistent with reduced antenna inductance caused by the metal sheet. This compares with driven four-strap array measurements, wherein 3% to 5% reduction in inductance was observed in the presence of plasma.¹² These results suggest a recipe for establishing a complex plasma surface impedance⁶: (1) set the metal wall gap for the right reactance; (2) interstice the resistive sheet to produce the right resistance; and (3) iterate as necessary.

Figure 3 exhibits the transmission passband modifications introduced when the TWA is driven by a TWR, as typified in Fig. 1. At the observed maximum TWR resonance (about 62 MHz), the roundtrip electrical length at midband (i.e., for 90 deg phasing/strap) was a little under 2 m, which is consistent with prediction.⁶ Furthermore, the observed maximum gain of 1.8:1 is consistent with prediction⁶ for a 0.7 roundtrip transmission efficiency and the 3 dB hybrid coupler.

3. CONCLUSIONS AND RECOMMENDATIONS

The reversible conversion of the B4C prototype in DIII-D to an externally tuned TWA has been discussed. Several critical enabling technologies have been demonstrated:

1. Tunability over 30 to 120 MHz using a line stretcher in each strap cavity.
2. Smooth phase change between $(0, \pi)$ cutoffs within a 2 MHz transmitter bandwidth.
3. Single pass transmission loss and passband modification caused by resistive and reactive sheet simulators of plasma loading.
4. Recirculating power gain in a traveling wave resonator (TWR) driven TWA.

Recommendations for future externally tuned TWA research tasks are:

1. Modify or delete the as-built septa and shields to improve phase control, stability, directionality and coupling to plasma.
2. Demonstrate the *in situ* conversion of a driven four-strap array to a TWA, as recently demonstrated with the Mock-up. Note in Fig. 4(a) that only two SWR locations need to be shorted. One tuned line inputs power, the other extracts power. A 3 dB hybrid coupler can be used to recirculate power.
3. Conduct near term 200 W experiments in DIII-D. Investigate how TWAs respond to plasma transitions and fluctuations in reactive and resistive loading.

Recommendations for alternative TWA concepts are:

1. Develop the present 9 to 27 strap "thin" combline TWA concepts^{5,6} for DIII-D. These comblines can fit in and between ports and tile surface to vessel wall recesses.
2. Study the hybrid TWA concept,¹³ that mixes features of the combline elements, as sketched in Fig. 4(b). This takes advantage of combline enhancements near a preselected frequency for FWCD, while retaining full conventional capability and broadband access to driven FWCD and ion/electron heating scenarios.
3. Design TWAs for two-strap center grounded arrays like those in TFTR and Alcator, and four Jet-type strap arrays like those being fabricated for DIII-D and JET.

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FIG. 1. A TWR driven TWA.

FIG. 2. TWA $|S_{21}|$ profiles parametric in (a) resistive and (b) reactive sheet loading.

FIG. 3. Observed TWR-TWA circuit gain.

FIG. 4. Conversion of the driven four-strap array in DIII-D to (a) an externally tuned TWA; (b) a hybrid thereof with combine TWA elements.

Table I. Parameters for the DIII-D Prototype and Mock-up

Antenna	ℓ_p (m)	v/c	Z_0 (Ω)	R' (Ω/m)	$k_{12}=k_{34}$	k_{23}	$k_{13}=k_{14}$	k_{14} (%)
Strap Proto.	0.45	0.52	42/93	—/0.015	9.5	7.4	1.6	0.4
Strap Mock-up	0.45	0.52	35/75	0.12/0.015	7.0	6.5	0.7	0.2
Strip Proto.	0.34	1	32	0.005				
Strip Mock-up	0.38	1	32	0.005				
Coax Proto.	*	1	30	0.086	*Strap 1=0.75; 2=0.82; 3=0.80; and 4=0.75 m			
Coax Mock-up	0.13	1	40	0.02				

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