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Development of Fast Wave Systems Tolerant of Time-Varying Loading*

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A new approach to fast wave antenna array design based on the traveling wave antenna has been successfully demonstrated on the JFT-2M tokamak. A traveling wave antenna is powered though a single feed and the power flow from element to element is only via mutual reactive coupling. A *combline* is a particular type of traveling wave antenna, in which only the fed element and the element at the downstream end of the array are connected to vacuum feedthroughs, while the intermediate elements are terminated with reactances inside the vacuum chamber. A twelve element combline for operation at 200 MHz was designed and fabricated at General Atomics, and installed and operated on the JFT-2M tokamak. The full output power of a single transmitter, 0.2 MW, was coupled to tokamak discharges with very little conditioning required. The input impedance of the combline was well matched to the transmission line impedance for all loading conditions, including vacuum (no plasma), Taylor discharge cleaning plasmas, and ohmic, L– and H–mode tokamak discharges with neutral beam heating *without any adjustment of tuning elements.*

1. TRAVELING WAVE ANTENNAS

A single element fast wave antenna can be characterized by a pair of scalar parameters, such as a resistive and reactive impedance. For a loop antenna in the Ion Cyclotron Range of Frequencies (ICRF), typically $R \ll \omega L$. When an array of such loops is operated with a phase difference between the currents in successive elements other than 0 or 180 degrees, a third parameter comes into play, which is the mutual reactance between elements. This reactance is generally inductive, particularly if the elements are equipped with Faraday shields. The usual ordering of these three impedances is $\omega M \ll R \ll \omega L$. This condition can be enforced for arbitrary M and R by connecting an adjustable reactance [1,2] ("decoupler") in parallel with the antenna terminals in such a way that the composite system of antenna and decoupler has an effective mutual reactance $\omega M_{eff} = \omega(M\text{-}M_d) \cong 0 \ll R$.

Three such systems with decouplers have been used to power three four-element array antennas on the DIII–D tokamak for some years [2,3]. The decoupling allows the use of a 90 degree hybrid junction in such a configuration that the transmitter output is completely isolated from changes in loading impedance that affect all four elements in the antenna in the same way. This property has enabled recent operation of these systems at the 3 MW level into ELMing H–mode discharges [4].

However, this system still can have a rather high standing wave ratio in the lengths of transmission line between the antenna and the hybrid junction outputs during transients in the antenna loading. The decoupler must be adjusted for any change in the mutual reactance between the antenna elements; changes in the mutual reactance are generally seen to accompany changes in resistive and reactive loading.

A system in which the standing wave ratio remains low in the entire transmission line system for any resistive and reactive antenna loading, requires fewer bulky, expensive, and trouble-prone adjustable tuning elements, and permits full power operation at a wider range of antenna array phasings can be obtained in the following way. By changing the sign and magnitude of M_d so that the effective

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mutual coupling between elements is *increased*, so that the decoupler becomes a coupler, and $\omega M_{eff} = \omega(M+M_c)$ with $M_c \gg M$, the power flow from element to element will be dominated by the mutually reactively coupled power. Since the coupling reactance is dominated by a term that is independent of the plasma condition, the input impedance of the element at the "upstream" end will be almost independent of the plasma load to the extent that $\omega M_{eff} \gg R$. This is the basic idea of the traveling wave array configuration, in which the array is fed at the upstream end only. The power flow from element to element is through mutual reactive coupling, and the input impedance of the array is virtually independent of the load condition, as R is now only a small perturbation to a single element in the array.

The traveling wave approach to array design can significantly reduce constraints on the design of fast wave arrays. This is especially true if the design criteria for a given application allow the use of a *combline* [5] traveling wave antenna. A combline can be distinguished from a generic traveling wave antenna by the number of vacuum feedthroughs — a combline is a traveling wave antenna with mutual reactance only on the vacuum side, so only one feedthrough at each end of the array is required. This provides great savings since the feedthroughs are one of the most complex, costly, and least reliable elements in an antenna. Since the input impedance of the structure is practically independent of plasma load, the input impedance can be matched to the characteristic impedance of the transmission line for all loading conditions. The power per feedthrough can be much larger than in a conventional antenna, assuming that the limiting factor is electric field. A large number of antenna elements allows the plasma loading of each element to be much smaller than in an array with a small number of elements, assuming the same total power is coupled to the plasma. This fact permits the array to be far from the plasma surface, leading to a lower heat load on the array. Furthermore, an optically opaque Faraday shield is practical, which can lower the plasma density around the radiating elements, and may permit higher electric fields in the antenna without breakdown than are indicated from the usual design rules. The antenna straps may be closer to the backplane, leading to the possibility of a much thinner radial build, which allows a greater freedom of design.

2. COMBLINE FOR JFT-2M

Design of a new antenna for the JFT-2M tokamak afforded the opportunity to demonstrate some of these advantages of the traveling wave approach. The antenna is designed to couple up to 0.8 MW at 200 MHz (the existing transmitter at JFT-2M consists of four 0.2 MW modules), at $k_{||}$ of 0.21 cm^{-1} ($n_{||}$ =5 at 200 MHz). A pair of existing feedthroughs were to be reused. The combline that was designed is comprised of twelve modules, each of which contains a current strap grounded at one end, open-circuited at the other, a backplane and a three-layer Faraday shield in front and on both sides of the current strap. The shield has two layers in front of the strap and a layer behind the strap, between the strap and the backplane. The purpose of the inner layers of the Faraday shield is to lower the characteristic impedance of the elements and thus minimize the peak electric fields in the structure, and also to provide the capacitative loading necessary to give the combline a non-vanishing bandwidth [6]. The plasma-facing part of the Faraday shield was made of molybdenum coated with a very thin layer of titanium carbide, and was shaped so as to function as a pair of segmented poloidal limiters for each module, to minimize the connection length and hence the stray plasma density at the strap surface. To further reduce the stray plasma density, graphite poloidal limiters were attached to the vacuum vessel wall at each end of the array. The modular antenna design, in which the twelve modules are individually bolted to a pair of toroidal rails inside the tokamak, facilitates installation and maintainance of the array. A photograph of the completed twelve-element array and the pair of associated limiters as installed in the JFT-2M vacuum vessel is shown in Fig. 1.

3. HIGH POWER OPERATION OF THE COMBLINE ON JFT-2M

For this initial set of high power experiments with the combline on JFT-2M, two 0.2 MW, 200 MHz transmitters were connected to the antenna, one at each end. Each transmitter was protected by a circulator. A directional spectrum could be produced by operating one transmitter only, with the power not radiated from the antenna being prevented from reaching the unused transmitter by the circulator. A non-directional spectrum could be produced by feeding both ends of the combline

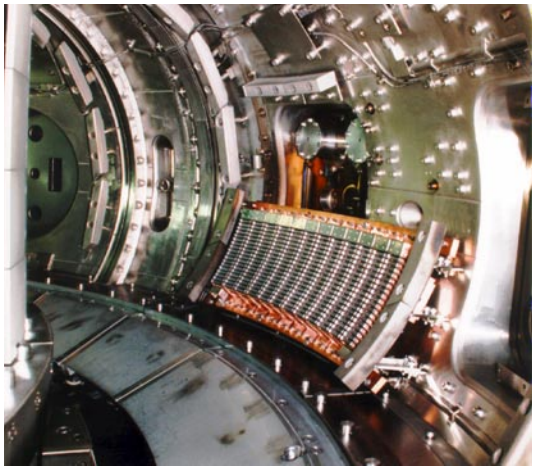

Fig. 1. The completed twelve-element array and the pair of associated limiters installed in JFT-2M.

simultaneously, and thus up to 0.4 MW could be applied to the antenna for testing its voltage limits.

In order to determine the $n_{||}$ that is coupled to the plasma and compare it with theoretical estimates, a scan of the antenna/plasma gap with ohmic tokamak plasmas was performed at a fixed input rf power level of 0.1 MW. Both the magnitude and phase of the transmission coefficient through the combline were measured as the gap was varied from 4 to 9.4 cm. The transmission coefficient magnitude can be related to the resistive loading per element (R) using estimates of the electrical parameters of each element. The decay of the resistive loading as the gap increases can be predicted from a simple model, assuming that the loading is entirely due to the fast wave, using estimates for the edge plasma parameters and normalizing to the measured R at one value of the gap. The experimental data on the magnitude of the transmission coefficient are shown in Fig. 2, along with the corresponding resistive loading per element and the model prediction. The agreement in the decay length between the model and the experiment is excellent.

As expected, the input impedance of the combline was well matched to the transmission line during all conditions studied, including all tokamak plasmas at any gap, in ohmic, neutral beam heated L–mode, and ELMing H–mode plasmas. This is illustrated in Fig. 3, where 1.8 MW of neutral beam heating sustains an ELMing H–mode plasma. The transmission coefficient drops during the short L–mode period from the value observed in the ohmic portion of the discharge, corresponding to increased resistive antenna loading. At the

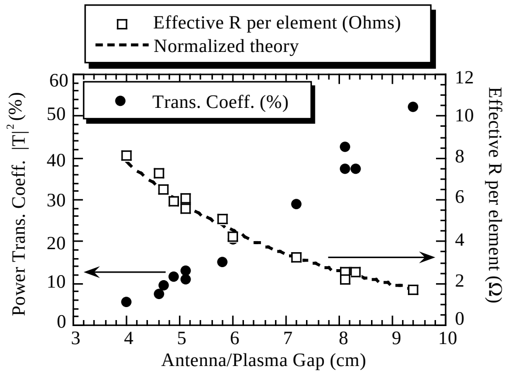

Fig. 2. Data from scan of plasma/combline gap with ohmic discharges, with I_p = 190 kA, B_T = 1.1 T, $\bar{n}_e \approx 1.9 \times 10^{19}$ m^{-3}, lower single-null divertor.

L/H transition, the loading decreases somewhat; at each ELM, the loading transiently rises. Throughout these loading variations, the reflection coefficient from the input of the combline is essentially zero. This was also true for the gap scan, during which the magnitude of the power transmission coefficient varied from 5 to 50% as the gap was increased.

The full output power of one transmitter (0.2 MW) was applied to the antenna without arcing under several different loading conditions. This power level could be sustained even without a plasma load, which corresponds to much higher electric fields in the antenna than are present with a plasma load. In double-ended (symmetric) operation, up to 0.25 MW was coupled to a tokamak plasma; the full two-transmitter output of 0.4 MW was coupled to Taylor discharge cleaning plasmas. These power levels were achieved after only a few half-days of vacuum (mostly multipactor) conditioning. It is important to note that no signs of reaching a power limit, other than the transmitter limits, were observed during this two week campaign. Reliable power handling was facilitated by the fact that since no tuners have to be adjusted at any time, short pulse high voltage vacuum conditioning can be continued up to a few seconds prior to the tokamak shot, and can be resumed immediately after the discharge. This method of maintaining antenna conditioning was applied throughout the high power phase of these experiments. Although the power levels injected into JFT-2M in these experiments were small compared to the multi-MW levels used on large tokamaks, as a result of the small size of the combline, the rf electric fields sustained without breakdown in these experiments actually exceeded the ITER electric field design criteria.

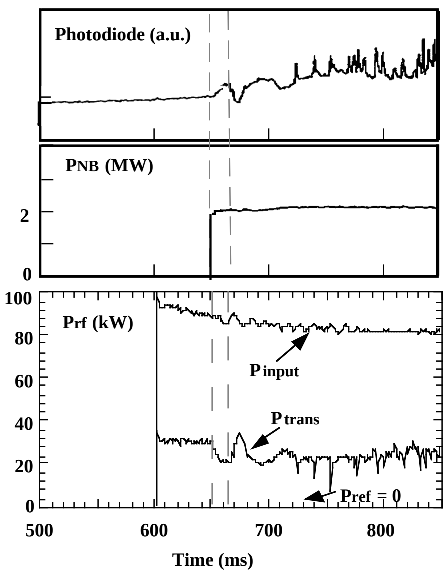

Fig. 3 Power into combline, reflected power from the input (zero), and the power not coupled to the plasma after one pass through the combline, P_{trans}, for a JFT-2M discharge with ohmic (600–650 ms), L–mode (650–665 ms), ELM-free H–mode (665–720 ms), and ELMing H–mode (720–850 ms) conditions.

4. SUMMARY, CONCLUSIONS, AND FUTURE WORK

Low power traveling wave antenna experiments on DIII–D [7] and the high power combline experiments on JFT-2M have demonstrated many of the possibilities of the traveling wave approach to antenna array design. In both cases, the input impedance of the structure was independent of the plasma conditions, and indeed, of whether or not a plasma load was present. The DIII-D experiments used existing antenna arrays, demonstrating the usefulness of this approach with existing conventional antenna arrays, while the JFT-2M case provided an opportunity to design a high power antenna based on the traveling wave concept from the outset. Some of the unique possibilities thus explored were: twelve antenna modules with only two feedthroughs, heavily Faraday shielded elements with light coupling per element and successful operation at antenna to plasma gap of up to 9 cm, up to 0.25 MW coupled to tokamak discharges in a symmetric spectrum using a pair of transmitters and up to the full single transmitter capability of 0.2 MW in a highly directional spectrum with very little antenna conditioning required. No tuning elements were adjusted at any time during the entire experiment.

Future experiments using the JFT-2M combline will use hybrid junctions to combine the four transmitters to work towards the demonstration of 0.8 MW operation of the combline. On DIII–D, several different plans for operating the existing four-strap antenna arrays as traveling wave antennas at high power are being considered. In any case, the relatively small radiation per pass through the antenna structure that is obtained with only four elements necessitates the use of a power recirculation system [5]. Such a resonant ring is characterized by a rather low Q even with only four elements, so that the resonance is not critical. A high power application of this transmission line topology to the existing antenna arrays on DIII–D would demonstrate the usefulness of this approach to existing antenna systems, such as on JET, Alcator C Mod, or to the ITER ICRF system even without any changes to the antenna design.

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