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GA–A22817

CONF-980130--

DEVELOPMENT OF IMPEDANCE MATCHING TECHNOLOGIES FOR ICRF ANTENNA ARRAYS

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GENERAL ATOMICS

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This is a preprint of an invited paper presented at the Second Europhysics Topical Conference on RF Heating and Current Drive of Fusion Devices, January 20–23, 1998, Brussels, Belgium, and to be printed in the *Proceedings.*

Work supported by
U.S. Department of Energy
under Contract DE-AC03-89ER51114

GENERAL ATOMICS PROJECT 3466
MARCH 1998

GENERAL ATOMICS

Development of Impedance Matching Technologies for ICRF Antenna Arrays

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Abstract

All high power ICRF heating systems include devices for matching the input impedance of the antenna array to the generator output impedance. For most types of antennas used, the input impedance is strongly time-dependent on timescales as rapid as 10–4 s, while the rf generators used are capable of producing full power only into a stationary load impedance. Hence, the dynamic response of the matching method is of great practical importance. In this paper, world-wide developments in this field over the past decade are reviewed. These techniques may be divided into several classes. The edge plasma parameters that determine the antenna array's input impedance may be controlled to maintain a fixed load impedance. The frequency of the rf source can be feedback controlled to compensate for changes in the edge plasma conditions, or fast variable tuning elements in the transmission line between the generator output and the antenna input connections can provide the necessary time-varying impedance transformation. In "lossy passive schemes," reflected power due to the time-varying impedance of the antenna array is diverted to a dummy load. Each of these techniques can be applied to a pre-existing antenna system. If a new antenna is to be designed, recent advances allow the antenna array to have the intrinsic property of presenting a constant load to the feeding transmission lines despite the varying load seen by each antenna in the array.

I. INTRODUCTION

All large tokamaks in the world (as well as most of the medium-sized facilities) are presently equipped with multi-megawatt Ion Cyclotron Range of Frequencies (ICRF) Fast Wave (FW) heating and current drive systems. In each installation, inductive loop antennas are used to excite the fast wave in the plasma. The antennas are deployed as phased arrays of two or four elements in the present-day experiments. The physics of the fast wave absorption has been recently reviewed [1,2], as has the interaction between the fast waves and the plasma edge [3]. The present review is of recent developments in technologies for adapting the input impedance of the antenna array to match the transmitter output impedance.

The reason that impedance matching is of great practical significance in the ICRF is that the maximum power that can be produced by the tetrode-based transmitters that are used is a strong function of the amplitude and phase of the standing wave ratio (SWR) at the transmitter output. A typical transmitter is capable of generating 2 MW into a perfect match (SWR of unity), but a power reflection coefficient of 10% (SWR ~ 2 in the output line) reduces the maximum power to as little as 1 MW; the extent of the power degradation depends on the phase of the mismatch at the tetrode. Hence, efficient utilization of the installed transmitter power requires an excellent impedance match at the transmitter (SWR < 1.25) at all times during application of high power FW injection.

Unfortunately, the basic physics of FW coupling to tokamak plasmas with inductive loop antennas leads to practical difficulties in achieving the necessary impedance match. Electrically, a single element of an array of loop antennas may be modeled as a length of transmission line (with a characteristic impedance not necessarily equal to that of the feed line) terminated with a lumped impedance $Z_T = R + jX$. In the absence of a plasma, the resistive part of this terminating impedance (referred to as loading or coupling impedance) represents ohmic losses in the antenna structure, which are generally quite small, so that R is typically a few tenths of an ohm. The effect of a plasma adjacent to the loop is to increase the resistive part of the loading impedance, since coupling to waves that carry energy away from the antenna is indistinguishable from increased losses in the circuit. In most tokamak experiments with ordinary loop antennas, the resistive loading is in the 0.5 – 10 Ω range. Since the characteristic impedance of the transmission lines used is in the range of Z_0 = 25 – 50 Ω, at all times $R \ll Z_0$. Generally, a change in the reactive part of the antenna loading is correlated with the increase in the resistive part; specifically, the electrical length of the antenna is usually slightly reduced in the presence of plasma.

The resistive part of the antenna loading may be written semi-quantitatively [4] as the first moment of the antenna spectrum convolved with the plasma surface impedance, as follows:

$$R \cong \frac{S}{\mu_0 I^2} \int_{k_z} \left|B_z(k_z, x=0)\right|^2 \exp\left[-2|k_z|x_c(k_z)\right] \mathrm{Re}\left[Z_p(x=x_c)\right] dk_z \ , \tag{1}$$

in which S is the surface area of the plasma, I is the antenna current; the first factor inside the integrand represents the spectrum excited just in front of the antenna; the exponential expresses the evanescence of the wave fields at densities less than the cutoff density, which is reached at $x = x_c(k_z)$. The final factor in the integral represents the real part of the plasma surface impedance $Z_p \equiv E_y/B_z$ evaluated at the location of the cutoff. The surface impedance is a function of k_z, the density gradient at the cutoff, the frequency, the ion mass, etc. The numerical value of the loading tends to be small (compared with Z_0) due to the exponential factor, because the absolute value of the exponent is greater than unity for most of the useful portion of the antenna spectrum. For a fixed antenna geometry and phasing, this expression shows that the loading depends most strongly on the distance between the antenna surface and the cutoff layer, and secondarily (through the surface impedance) on the slope of the density profile in the neighborhood of the cutoff. In tokamaks, the edge density profile depends on a large number of poorly controlled parameters, such as the history of the wall conditions (recycling level), the particle confinement of the bulk plasma (auxiliary heating power level, current, L– or H–mode, Edge Localized Modes [ELMs], etc.), and on nonlinear effects of the FW power itself (gas release, impurity influx, ponderomotive effects, etc.). Since the particle confinement time in the edge plasma is quite short, the variations of the edge density are rapid and large, which in turn results in rapid and large variations in the antenna loading. In short, the two most important properties of the resistive loading of a conventional loop antenna are that it is *low* ($R \ll Z_0$) and it is *highly variable* on a wide range of timescales.

In tokamaks operating in H–mode, wide variations in antenna loading are observed within the discharge. The minimum values of R are generally observed in ELM-free H–mode, in which the distance to the cutoff tends to be fairly large, and the density gradient quite steep near the cutoff, while the loading peaks during giant ELMs at a value which can be a factor of 2 to 5 times higher than between ELMs [4]. The sudden decrease in antenna loading that accompanies the L–mode to H–mode transition typically occurs on a timescale of a few milliseconds, as does the increase in loading at the H– to L–mode transition. The timescale of the changes in R caused by an ELM has been measured on ASDEX Upgrade [5] and on JET[[6] with high time resolution. In both cases, the rise in loading occurs on a time scale of ~100 μs, and the loading subsequently decays on a time scale of a few milliseconds. This sub-millisecond timescale represents a challenge to any dynamic impedance matching scheme.

In the remainder of this paper, five general approaches to achieving the required impedance matching on fast time scales are reviewed. Perhaps the most direct approach is to control the plasma edge parameters themselves to maintain a constant R through the exponential and surface impedance factors in the above equation. The parameters of the generator, most usefully the frequency, can be rapidly feedback controlled to assist in impedance matching. The impedance matching network can be adjusted in realtime in an attempt to track the variations in the antenna loading. A fourth family of techniques, which may be called ''passive lossy matching schemes'' is to divert reflected power into a dummy load, and thus isolating the transmitter from the variations in the loading impedance. Finally, it is possible to construct antenna arrays in such a way that the input impedance of the array is nearly independent of the loading of each element in the array, based on the ''traveling wave antenna'' concept. Each of these methods has important applications in modern FW systems, and these methods can be combined in various ways, depending on the precise constraints and desired operating space of the system.

II. ACTIVE CONTROL OF THE ANTENNA LOADING

For antenna arrays wide enough to launch a well-defined parallel wavenumber k_z, the resistive loading depends exponentially [see Eq. (1)] on the distance between the antenna surface and the cutoff, as demonstrated experimentally on JT-60U, for example [7]. This suggests that a decrease in loading due to a steepening of the density gradient near the cutoff may be compensated by moving the plasma edge closer to the antenna. A realtime feedback scheme can be implemented in which the radial position of the plasma, controlled by the vertical field system, is adjusted to maintain a constant resistive antenna loading. Such an arrangement was developed at JET [8]. An example in which the loading was kept at a constant value during an L– to H–mode transition by radial position feedback is shown in Fig. 1. In this case, variation of the reactive component of the antenna loading caused by the changes in the antenna/plasma gap is also compensated by a frequency feedback system (see Sec. III below). Other tokamaks that have used antenna/plasma gap control to maintain constant antenna loading include DIII–D [9], Alcator C Mod, and TFTR.

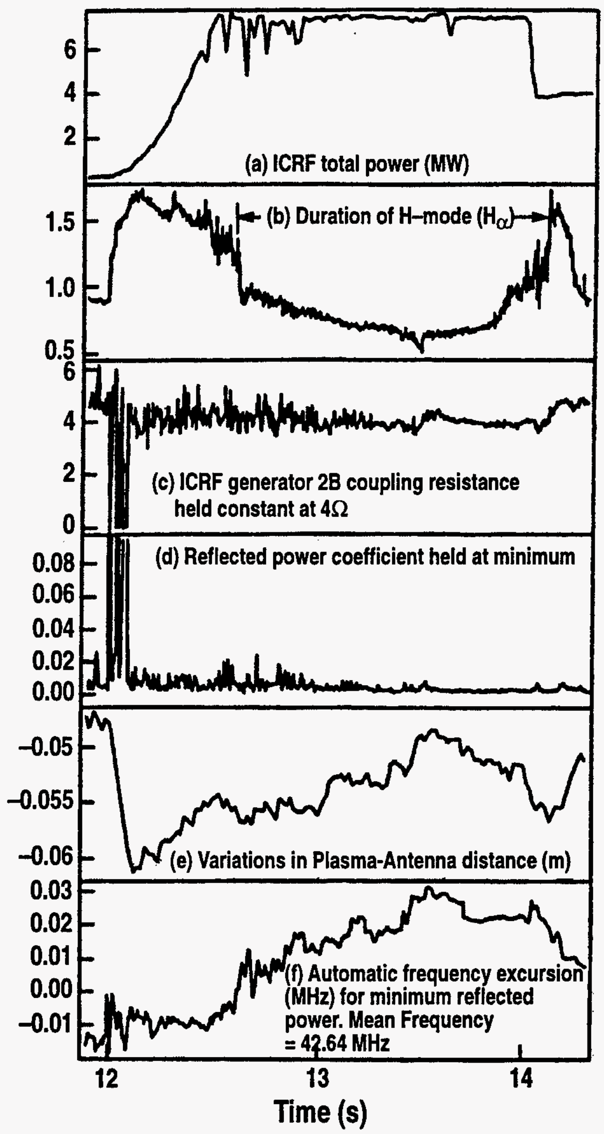

Fig. 1. Application of simultaneous antenna loading control and automatic frequency feedback control on JET to heat a discharge with an L–mode to H–mode transition (from Ref. 8).

The principal advantage of this direct approach to the impedance matching problem is the fairly fast time response (better than ~10 ms) that can be achieved, although ELMs are too fast to be compensated by this method. The loss in experimental flexibility that inevitably results from application of this method has precluded its wider application — for example, many experiments require that the plasma/antenna gap be kept constant for diagnostic reasons or at least kept greater than some minimum distance to avoid strong plasma/wall interactions. Other methods of controlling the edge density profile have been used in the lower hybrid range of frequencies with some success, such as gas puffing near the antenna to maintain high loading, but have not been tried in the ICRF for various reasons.

III. FEEDBACK CONTROL OF GENERATOR PARAMETERS FOR IMPEDANCE MATCHING

This class of technologies is based on the fact that the frequency and phase of the transmitter output can be controlled on a timescale of a few microseconds. In the case of frequency feedback control for impedance matching, the idea is to arrange the transmission line and matching network in such a way that some particular type of loading change can be compensated by a variation of the frequency within the instantaneous bandwidth of the transmitter. As already mentioned, such a scheme has been in use at JET for some time [8]. Subsequently many other laboratories have implemented or studied frequency feedback schemes. An application of frequency feedback from JT-60 [10] is shown in Fig. 2. In this example, the resistive loading changes by about a factor of two; the frequency feedback maintains a low reflection coefficient throughout. Another example of the use of frequency control as a means of fast impedance matching is the "twin stub" of Kumazawa et al. [11]. This device is electrically equivalent to a very long short-circuited stub. By making this one reactance much more frequency sensitive than any other element in the system, a frequency-controlled reactance is produced. By appropriately choosing the other electrical lengths in the system, a particular type of loading variation can be compensated on a short timescale using a suitable feedback controlled frequency.

Another scheme of this general type, proposed in Ref. 4, would use feedback control of the phase difference between array elements to maintain a constant resistive loading, thus taking advantage of the strong k_z dependence of the loading (see Eq. 1). This is possible in a situation where each array element is powered with its own high power transmitter, because the phase between transmitters can be controlled at the low power end of the amplifier chains [8]. This proposal has not yet been tested. Its main disadvantage is that the response to a decrease in resistive loading, *e.g.*, at an L–to–H transition, would be to decrease the peak coupled $|k_z|$, which may have an undesirable effect on the wave absorption in the plasma.

The fundamental limitation of this class of technology as an impedance matching tool is that the antenna loading is a complex quantity, hence two independent controls are necessary to fully compensate arbitrary loading variations. Either frequency or phase variation alone

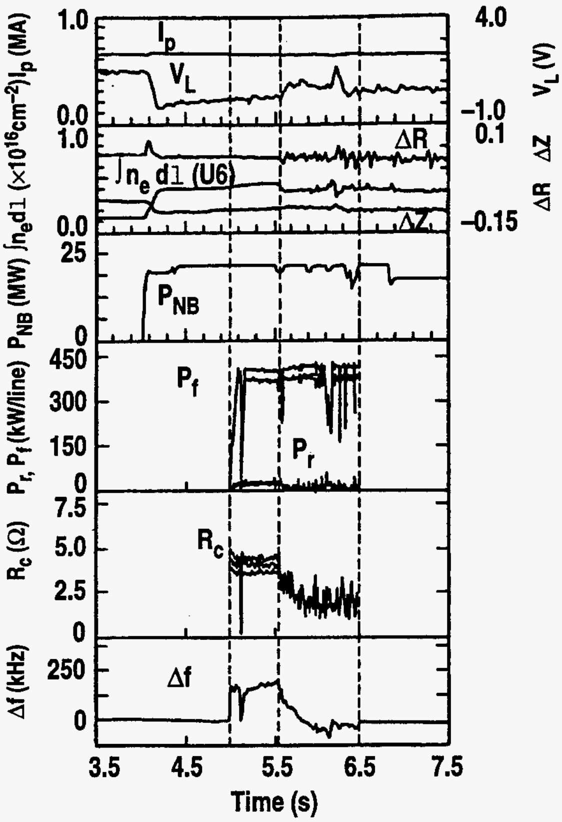

Fig. 2. Application of frequency feedback control on JT-60 (from Ref. 10). The reflected power P_r is kept low despite the nearly factor-of-two decrease in the loading resistance R_c after 5.5 s by variation of the transmitter frequency, Δf.

provides only a single control. A potential obstacle to the application of frequency control is that most of the high power transmitters in use have quite limited instantaneous bandwidth at full power — the JET transmitters are, by comparison, exceptionally wideband. Even with a relatively wideband transmitter, long transmission lines at high SWR are required for this system to be practical, with the accompanying undesirable ohmic losses in these lines. The great advantage of this scheme over any other dynamic impedance matching scheme is the submillisecond response time that is possible. This is the only dynamic technique fast enough in principle to track the rise of an ELM. However, since another control is necessary to cope with arbitrary loading variation, development of a second fast tuning method is required.

IV. FAST ELECTROMECHANICAL IMPEDANCE MATCHING NETWORKS

An impedance matching network consists of a small number of adjustable reactances connected to the transmission line between the generator and the load (in this case, the antenna array). In the ICRF, these reactances are most commonly made as short-circuited lengths of transmission line (stubs) connected in parallel to the main transmission line; the reactance is varied by adjusting the length of the stub. By careful design, it has proven possible to make such stub tuners variable on a time scale of a few seconds [8]. One difficult aspect of this design is to make a reliable high-current sliding connection that can be both moved rapidly and survive a large number of cycles of motion. This has been solved in some cases by making the short circuit capacitatively so that direct physical contact is not required [12], or by producing the variation in electrical length by changing the level of a dielectric fluid [13].

Instead of varying a stub's electrical length, a variable capacitor can be used as the adjustable reactance in the tuner. The physical distance that the capacitor electrodes must be moved to yield a significant reactance change can be made quite small, so that a much higher tuning speed is possible. Such a system is in routine use on TEXTOR [14]. In this case, a pair of vacuum variable capacitors are configured as the movable parts of a double stub tuner. A characteristic tuning time of about 40 ms has been achieved, as shown in Fig. 3. On Tore Supra, vacuum variable capacitors are built into the antennas themselves; in this way the vacuum feedthroughs and the entire transmission line to the transmitters are all at the minimum peak voltage and the minimum ohmic losses for a given power level. Optimization of the drive mechanism for these capacitors has led to the demonstration of automatic matching with a time response of about 200 ms [15].

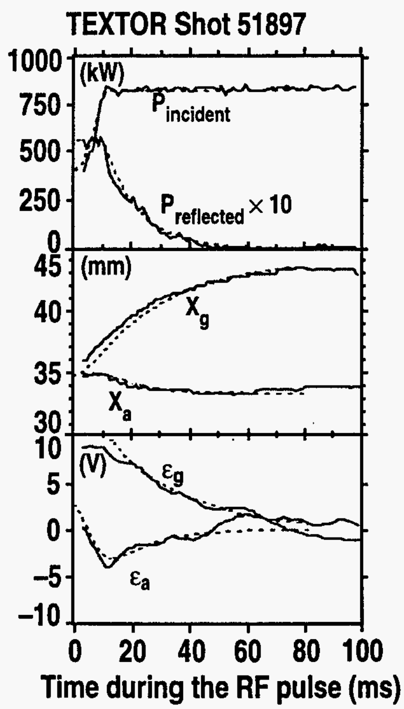

Fig. 3. Achievement of ~40 ms response time with automatically controlled double stub tuner with vacuum variable capacitors on TEXTOR (from Ref. 14). The reflected power ($P_{reflected}$) is reduced to zero on this time scale by the motion of two vacuum variable capacitors, the positions of which are shown as X_g and X_a; the respective error signals for the feedback loop are shown as ε_g and ε_a.

The electrical length of a stub tuner can be varied by changing the magnetization of a ferrite material filling the stub. The advantage of such a device is the lack of any moving parts — the speed of the tuner is limited only by the inductance of the magnetizing coils and eddy currents in the structure. A low power prototype double stub tuning system of this kind was demonstrated on DIII–D in 1992 [16]. A matching timescale of about 20 ms was shown. More recent work has resulted in a high power system in which the response time has been reduced to about 4 ms.

Clearly, no electromechanical scheme by itself is rapid enough to track the rise of antenna loading caused by a giant ELM. However, the judicious combination of any of the rapid electromechanical schemes with fast frequency control can yield a dynamic tuning system that is capable of matching arbitrary loading changes on a submillisecond timescale, provided only that the most rapid changes are a reproducible mixture of resistive and reactive loading changes [17]. This constraint would be satisfied by a quasi-steady state ELMing H–mode, for example.

PASSIVE LOSSY MATCHING SCHEMES

A rather different kind of solution to the fast impedance matching problem is to divert reflected power away from the transmitter output into a dummy load. The prototypical example of such a ''passive lossy scheme'' is the Y-junction circulator at the transmitter output. Such devices are used in many high power lower hybrid current drive systems at frequencies in the 0.8 – 5 GHz range to protect the klystrons from reflected power. Apparently, the large size and narrowband character of a high power Y-junction circulator for frequencies in the ICRF has so far prevented the application of this simple idea in FW experiments with one exception — the 200 MHz FW experiments in the JFT-2M tokamak, in which the four 0.2 MW transmitters are each protected by narrowband circulators [18]. However, long pulse high power circulators are practical for frequencies in the upper part of the ICRF [19], and the attractiveness of such a simple solution to the dynamic impedance matching problem — the time response to changes in the reflected power is effectively instantaneous — merits a re-examination of this approach, particularly for fixed frequency systems above ~50 MHz.

The Y-junction circulator is a ''non-reciprocal'' device, *i.e.*, its electrical properties depend on the directions of wave propagation with respect to its ports. It is possible to construct a passive lossy system with only reciprocal components, based on the 3 dB 90° hybrid junction, provided that the antenna system can be divided into two subsystems with the following properties: (1) there is negligible net resistive or reactive coupling between the two subsystems, (2) the complex input impedances of the two subsystems are identical, and (3) it is either required or at least tolerable that the two subsystems be excited with equal amplitudes at a relative phasing of 90°. This possibility derives from a well-known property [20] of the 3 dB 90° hybrid junction: that if the two output ports are terminated with arbitrary *identical* impedances and one of the two input ports is matched with a matched load, the remaining port is matched. Since the ideal hybrid junction is lossless, any power reflected from the two identical subsystem impedances is dissipated in the matched load.*

Application of this idea to FW antenna arrays generally requires a method of canceling the mutual reactance that naturally exists between toroidally adjacent elements of the array. Such a "decoupler" was applied to a two-element array on the Phaedrus-T tokamak [21]. Other forms of decouplers constructed from standard transmission line components have been designed for JET [22] and still other decouplers are used on the DIII–D FW systems 23,24].

A very simple passive lossy matching system is in use on a four-element FW array at 60 MHz on DIII–D [25]; this system requires only a single adjustable tuning element, and is illustrated in Fig. 4(a). In this case, 90° progressive phasing on the array elements is desired for current drive experiments. Resonant loops of transmission line connected between alternate elements produce 180° phase differences between elements 1 and 3, and between 2 and 4. The two resonant loop feed points are connected with a decoupler to null out the mutual reactance between the two ports. Quarter wave transformers provide an impedance match for a nominal value of the antenna loading. The two inputs on the generator side of the transformers constitute the identical uncoupled impedances that are connected to the two outputs of a 3 dB 90° hybrid junction. The 90° phase difference between those two ports yields the desired (0°, 90°, 180°, 270° antenna phasing. The exact left-right symmetry between the two halves of the antenna and transmission line system provides the necessary balance so that the input of the hybrid junction is always matched given that the mutual coupling is nulled out. Since the mutual reactance between the array elements also depends on the edge plasma parameters [21], the decoupler must be variable — the decoupler stub is the only adjustment in the system. The response of the system to a vigorously ELMing H–mode plasma is shown in Fig. 4(b). Despite factor-of-four variations in the resistive antenna loading due to ELMs, the reflected power fraction seen at the generator output remains less than 2.5% (SWR < 1.4) at all times. A voltage limiting circuit is also in use in this example; the consequence of lower generator reflected power and limited electric fields in the antenna is that there are no generator or arc trips interrupting this pulse.

Another application of the passive lossy scheme based on the hybrid junction is the system in use at ASDEX Upgrade [26]. In this case, each of the two identical subsystems consists of a two-element antenna array and a matching network. Symmetry between the two subsystems is obtained by adjusting the matching networks so that they are identical; to date, adequately low mutual coupling between the arrays has been achieved by choosing a pair of arrays that are physically far apart in the tokamak. This system is presently in use on all four two-element arrays on ASDEX Upgrade; each pair of arrays is powered with the combined output of two 2 MW transmitters. Much more reliable performance in ELMing H–mode

*3 dB 90° hybrid junctions have been applied in the DIII–D ICRF systems since 1988; this property was observed experimentally when a decoupling network was installed in 1993. Systematic exploitation of this property for ICRF antenna array systems was described by R. H. Goulding *et al.* in 1995 [27].

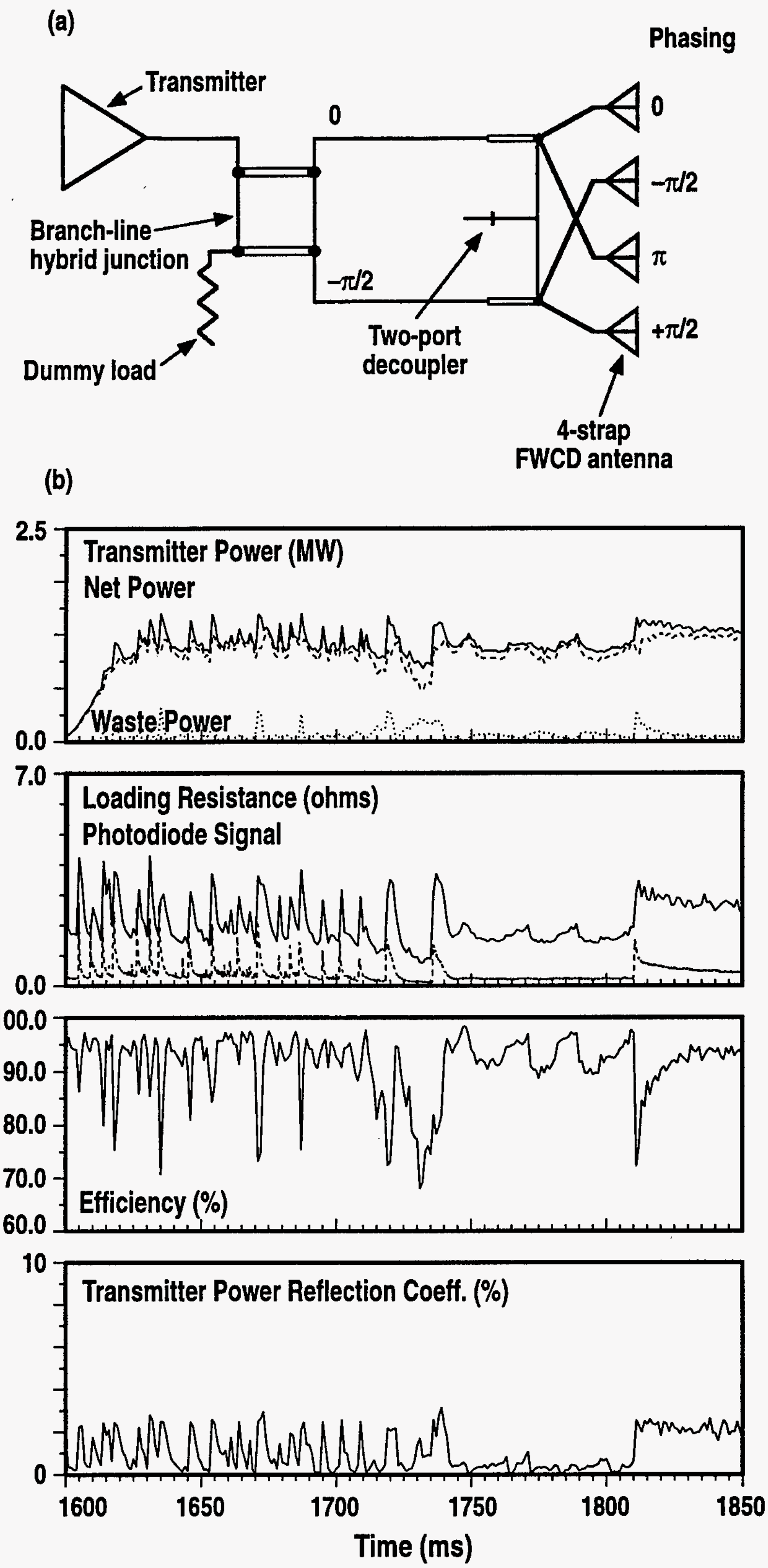

Fig. 4. (a) Schematic of the Balanced Feed Configuration (BFC) [25] used on DIII–D. (b) Response of the BFC to vigorously ELMing H–mode discharge.

plasmas has been obtained, compared with the previous system without hybrid junctions. Future plans call for powering adjacent arrays for FW current drive experiments. The larger mutual coupling between the two arrays will then necessitate a decoupler network, which will make the system very similar to the DIII–D configuration discussed above. Other hybrid-based passive lossy schemes have been proposed for future systems [27,28].

VI. TRAVELING WAVE ANTENNAS

In practice, the ultimate limit on power that can be coupled reliably with a loop antenna appears to be related to the peak rf electric field that appears in the structure. The simplest way of increasing the power handling capability of an array is to increase the number of loops in the array, so that the maximum electric field appearing in any element can be kept within limits while increasing the total power. However, a large number of rapidly variable matching networks is probably impractical, limiting the maximum number of elements in an array. What is necessary for an array with significantly more than about four elements is a means of performing the power division and phase control internally to the antenna structure, analogous to the multi-junction grills used in lower hybrid experiments. It would also be a very desirable property of such a large-array solution if the input impedance of this structure could be made to be independent of the resistive loading per element.

A method for achieving these goals is to convert the toroidal array of loop antennas into a slow wave structure [29], which has been called a traveling wave antenna (TWA). The power is applied to the array element at one end of the array (the ''upstream'' end), and the power is coupled to the next element by the mutual reactance between the elements. A small fraction of the power is radiated from each element. At the ''downstream'' end of the array, any unradiated power must be either removed or dissipated in a matched load. The simplest circuit model of a traveling wave antenna is illustrated in Fig. 5, in which a toroidal array of loop antennas is idealized as a semi-infinite series of one-turn transformers, each coupled only to its nearest neighbors via the mutual reactance M. The resistive loss in each loop, R, represents the sum of the ohmic loss in the loop and the resistive loading of the loop. This model corresponds to operation at the self-resonant frequency of the loops, at which the reactances due to the loop's self-inductance and capacitance cancel. If the resistive impedance is much smaller than the mutual reactance ($R \ll \omega M$), then the current in each element leads its downstream neighbor by 90°. The input impedance of this structure is approximately [30]

$$Z_{in} = \frac{V_{in}}{I_{in}} = \omega M \left[1 - \frac{1}{8} \left(\frac{R}{\omega M} \right)^2 + \ldots \right] , \qquad (2)$$

which is indeed nearly independent of the resistive loading provided that the mutual reactance dominates. In practice, a finite length TWA must be either long enough (sufficiently many

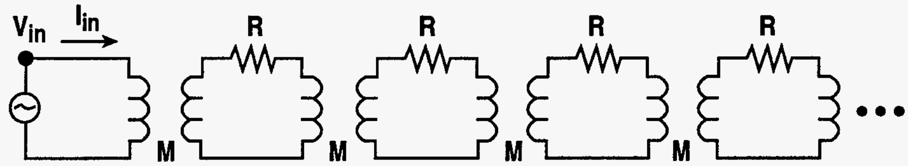

Fig. 5. Simple circuit model of a semi-infinite traveling wave antenna.

elements) that negligible power remains at the downstream end or provision is made to remove the unradiated power from the downstream end, so that the array is effectively infinitely long.

The physical realizations of a TWA are of two types, differentiated by the method by which the array elements are made resonant. In one approach, termed the ''combline'' [29] due to its close relationship with a type of microwave filter of that name, the antenna elements are made self resonant by capacitatively loading the loops within the vacuum vessel. These capacitances can be either lumped at one end of the loops or distributed along the loop by proper design of the Faraday screen [31]. The advantage of the combline over any other scheme of array operation is that no vacuum feedthroughs are necessary except for one at the upstream end and possibly one at the downstream end. The simplicity and cost reduction gained by the removal of all but two of the feedthroughs allows practical consideration of arrays with a much larger number of simple, modular, all-metallic elements than the two or four used in existing high power arrays.

Such a modular combline antenna with twelve elements and two vacuum feedthroughs was designed and built by General Atomics for the JFT-2M tokamak [32] where it has been used for FW current drive experiments at 200 MHz. Power levels up to 0.4 MW have been coupled with this small (0.2 m^2) array to date. Experiments have demonstrated that the input impedance of the array is indeed independent of plasma conditions, or even whether or not a plasma is present. This is shown in Fig. 6, where the power reflected from the input is zero during ohmic, neutral-beam-heated L–mode, and ELMing H–mode portions of a JFT-2M discharge. In this case, the power not radiated in a single pass through the antenna is deposited into a matched load connected to the downstream end of the antenna. The power dissipated in this load, also shown in the figure, is inversely proportional to the resistive loading per element of the array. The usual transient increases of loading at each ELM are evident.

In the second type of TWA, the loops are resonated with reactive components (usually lengths of transmission line) external to the vacuum vessel. The net mutual reactance between the array elements can be modified by connecting reactances between the resonant sections. The principal advantage of this approach over the combline is that the parameters of the TWA (resonant frequency, bandwidth) can be changed without modifying the antenna itself, while each array element requires a feedthrough in this ''externally resonated TWA'' just as in a conventional array. Application of the fast impedance matching technologies

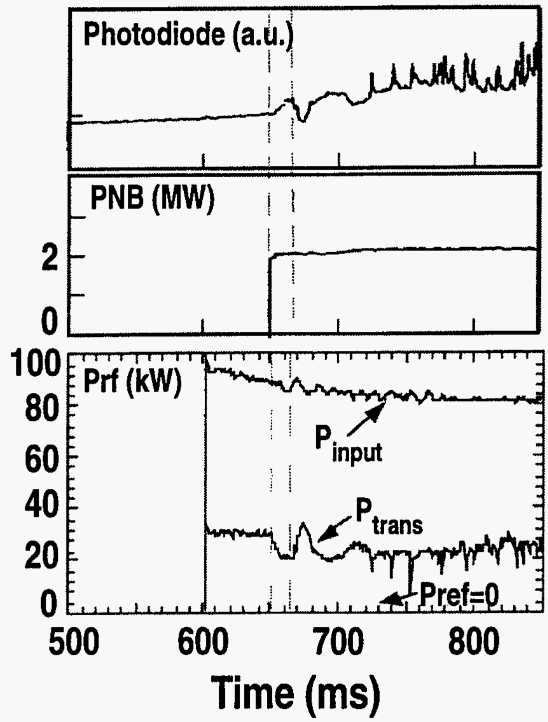

Fig. 6. Power into the upstream end of a twelve-element combline on JFT-2M (P_{input}), reflected power from the input (zero) and the power not coupled to the plasma after one pass through the combline, P_{trans}, for a discharge with ohmic (600–650 ms), L-mode (650–665 ms), ELM-free H-mode (665–720 ms) and ELMing H-mode (720–850 ms) conditions (from Ref. 32).

described in earlier sections of this paper could make these TWA parameters variable in real time.

One of the four-element FW antenna arrays on the DIII–D tokamak was connected as an externally resonated TWA for a low power test of this concept with plasma loading [33]. Three different levels of mutual coupling between the elements were compared. If no external mutual coupling is added to the ''natural'' coupling between the loops (narrowest bandwidth), the fraction of the incident power coupled to the plasma in one pass through the TWA is maximized, but the system's input impedance is very sensitive to reactive loading changes. At the other extreme, where low inductance connections are made between the resonant lines to maximize the mutual coupling, the input impedance is completely independent of the plasma loading, but very little power is coupled to the plasma in a single pass through the TWA. By increasing the inductance of these external links (decreasing the effective mutual coupling), a compromise was found, in which the reflection coefficient from the input remains less than 2% even at the peaks of the ELMs, and is less than 1% even after the discharge terminates, while the percentage of the input power that is coupled to the plasma in one pass through the TWA is larger than 50% through most of the discharge, as shown in Fig. 7. A high power version of this system has been designed and built [34], using only standard transmission line components and incorporating a variable power recirculating system [29,33].

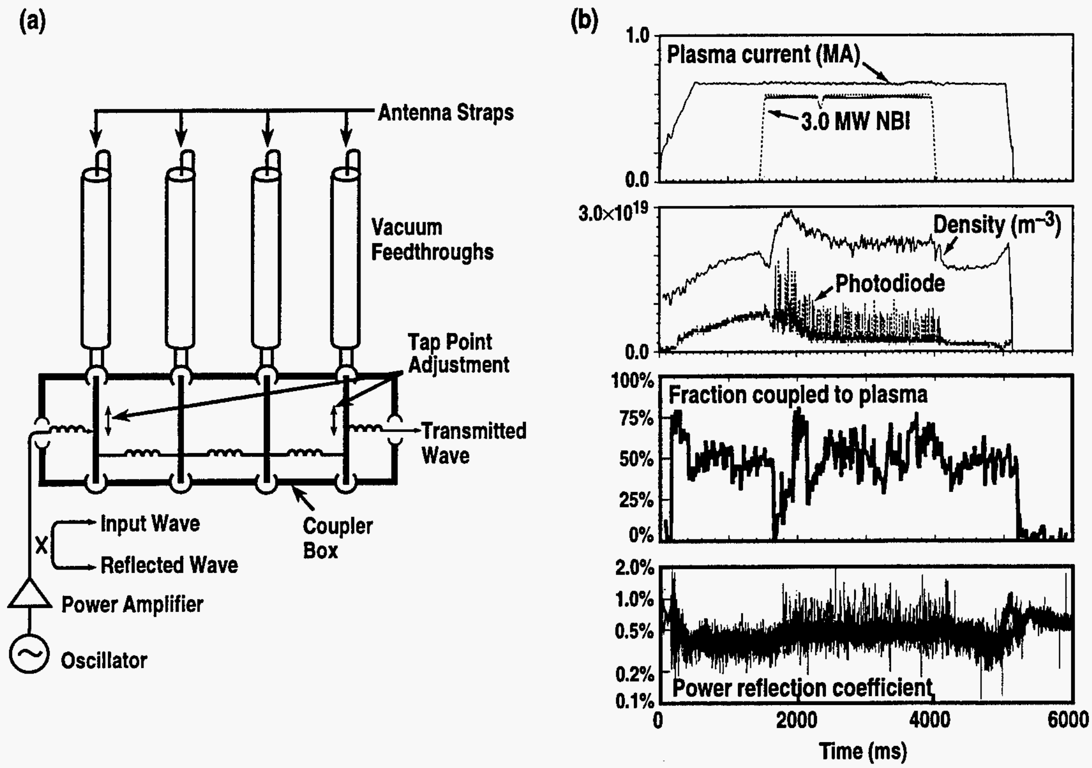

Fig. 7. (a) Traveling wave connection of a four-element FW array on DIII–D. (b) Fraction of incident power coupled to the discharge in a single pass through the TWA and the power reflection coefficient from the upstream end during and after a DIII–D discharge with ELMing H–mode conditions (adapted from Ref. 33).

VII. ARC PROTECTION WITH FAST IMPEDANCE MATCHING

One important point for any automatic fast matching scheme is the question of arc protection. In all conventional high power ICRF systems, breakdown in the antenna or the transmission lines is detected by the sudden change in reflection coefficient associated with the arc. Upon detecting a breakdown, the high power transmitter is shut off on a time scale of ~10 μs to limit the energy deposited in the arc. If, however, the impedance matching circuit is fast enough to match the arc's impedance prior to the protection system's response, damage to the antenna or transmission lines may result. Hence, arc protection systems that are not based on the magnitude of the reflection coefficient are an essential adjunct to any automatic fast matching system. Arc detection systems have been developed that are based on phase measurements [35,36], balanced loading between identical elements [8,27], rf emissions from the arc at frequencies other than the transmitter frequency [37-40], anomalously high antenna load resistance (DIII–D), pressure measurements on the vacuum side of the feedthroughs [35], optical emissions from the arcs [10], and sound emissions from arcs in the pressurized transmission line [40]. Space limitations do not permit further discussion of this important and rapidly developing topic here.

VIII. SUMMARY AND CONCLUSION

A wide variety of technical solutions to the problem of FW antenna array impedance matching have been developed over the past decade. In this paper, these solutions have been divided into five categories: (1) direct control of the plasma edge to control the antenna loading itself, (2) feedback control of generator parameters, most usefully the frequency to assist in impedance matching, (3) dynamic control of the impedance matching network to track time-varying antenna loading, (4) passive lossy matching schemes, either with non-reciprocal circuit elements or 90° hybrid junctions and requirements on symmetry, or (5) traveling wave antennas of either the combline type or the externally resonated TWA. These solutions have differing ranges of applicability, depending on the needs of the particular experiments and the characteristics of the available high power rf transmitters. In practice, parts of these solutions may be combined, such as the use of a fast stub technology for the decoupler in a passive lossy matching scheme, the combination of a fast vacuum variable capacitor with (much faster) frequency feedback [41], or the combination of feedback control of the plasma/antenna gap with frequency feedback, as in Fig. 1.

As has been shown in this paper, progress in the development of fast impedance matching tools in the past decade has been substantial. New systems can be designed (*e.g.*, ITER [27], NSTX [42]) incorporating these technologies with a high degree of confidence in their performance with time-varying loading. In present day experiments, each of these technical advances has increased significantly the range of physics problems that have been studied with reliable high power FW heating and current drive, as is evident from other contributions at this conference.

ACKNOWLEDGMENTS

The author gratefully acknowledges the contributions to this work by other members of the DIII–D RF Physics and Technology Division over the past decade. In particular, this paper is dedicated to the memory of Dr. David A. Phelps (1942–1997).

This is a report of work supported by the U.S. Department of Energy under Contract No. DE-AC03-89ER51114.

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M98004679

Report Number (14) GA-A22817
CONF-980130--

Publ. Date (11) 199803
Sponsor Code (18) DOE/ER, XF
UC Category (19) UC-400, DOE/ER

DOE