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DESIGN AND CONTROL OF PHASED ICRF ANTENNA ARRAYS*

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ABSTRACT

Phased antenna arrays operating in the ion cyclotron range of frequencies (ICRF) are used to produce highly directional wave spectra, primarily for use in current drive experiments. RF current drive using phased antennas has been demonstrated in both the JET[1] and DIII-D[2] tokamaks, and both devices are planning to operate new four-element arrays beginning early next year. Features of antenna design that are relevant to phased operation and production of directional spectra are reviewed. Recent advances in the design of the feed circuits and the related control systems for these arrays should substantially improve their performance, by reducing the coupling seen by the matching networks and rf power supplies caused by the mutual impedance of the array elements. The feed circuit designs for the DIII-D and JET phased antenna arrays are compared. The two configurations differ significantly due to the fact that one power amplifier is used for the entire array in the former case, and one per element in the latter. The JET system uses automatic feedback control of matching, phase and amplitude of antenna currents, and the transmitter power balance. The design of this system is discussed, and a time dependent model used to predict its behavior is described.

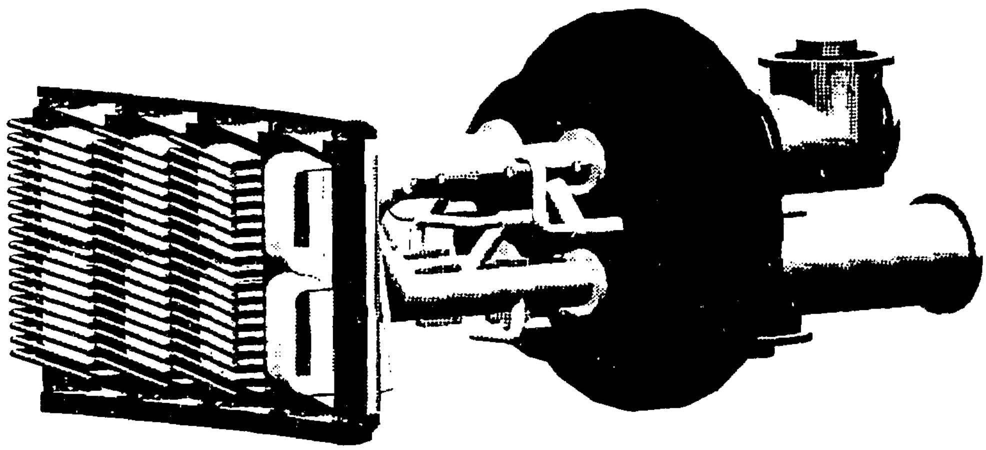

Fig. 1. Conceptual design of a modular four-element FWCD antenna array for DIII-D. This array is designed to operate at 4 MW for pulse lengths of 10 s in the frequency range from 30 to 120 MHz.

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DESIGNING ANTENNAS TO PRODUCE DIRECTIONAL SPECTRA

The current drive efficiency will be maximized by a design that launches waves at the peak $n_\parallel$ in the plasma for FWCD while simultaneously minimizing the power launched in the opposite direction. The variables affecting antenna directionality are the number and width of array elements, the location of the return currents, and the distance from the antenna to the edge of the plasma.

The number of array elements is often limited by the port geometry, as is the case for the new DIII-D antennas (see Fig. 1). The size of the port limits the number of elements to four for practical transmission line sizes. With the number of elements fixed, the size of the opening in the first wall determines the width of an element in DIII-D.

For identical, equally spaced antennas, the wavenumber spectrum of an antenna array can be written as $G(k_\parallel) = A(k_\parallel) \cdot F(k_\parallel)$, where $k_\parallel$ is the toroidal component of the wavenumber, $F(k_\parallel)$ is the spectrum of a single element of the array, and $A(k_\parallel)$ is the array factor [1,2], given by

$$A(k_\parallel) = \sum \exp[i(k_\parallel m w - m\Delta\phi)]$$

where the summation is over the m elements in the array, w is the width of an element, and $\Delta\phi$ is the relative phase between adjacent elements

A single element in the case of a loop antenna consists of a single loop and the sidewalls enclosing it. For the single-element spectrum, consider two limiting cases: one with bare current straps and return currents sufficiently removed radially from the plasma that their effect can be neglected, and one with return currents of equal magnitude at the same radial position as the current strap. Any practical antenna design will lie between these two. Figure 2(a) shows the spectrum for the two single-element cases at 2 cm in front of the current strap. The spectrum for the case with side walls was taken from a measurement on a mock-up antenna with the dimensions indicated. Figure 2(b) shows the array factor for a four-element array for 90° phasing. Figure 2(c) then shows the resulting array spectra for both cases.

Clearly the bare current strap array (no side walls) produces the more directional spectrum, however, the difference inside the plasma is reduced somewhat by the greater attenuation of the negative high-$k_\parallel$ peak resulting from its larger evanescent distance to the cutoff density layer. There is a key tradeoff between the greater directionality with deeply recessed sidewalls and the mutual coupling between adjacent elements. Using standard feed circuits, the mutual coupling between elements must be below a certain critical value, depending on plasma load, for stability of the phasing [3]. Decoupler circuits, discussed below, have been developed to get around this problem and allow the use of more highly coupled antennas. Figure 3 is a plot of the $k_\parallel$ spectrum in the plasma for DIII-D parameters and antenna geometry with side walls, where the desired peak predominates as a result of the greater evanescence of high $k_\parallel$ spectral components..

Increasing the gap between the plasma and the antenna increases the directionality but reduces the plasma loading. The gap is optimized when the loading is barely sufficient to launch the full transmitter power without breakdown. Thus, for current drive applications, particular emphasis must be placed on making the voltage limits of the antenna as high as practicable.

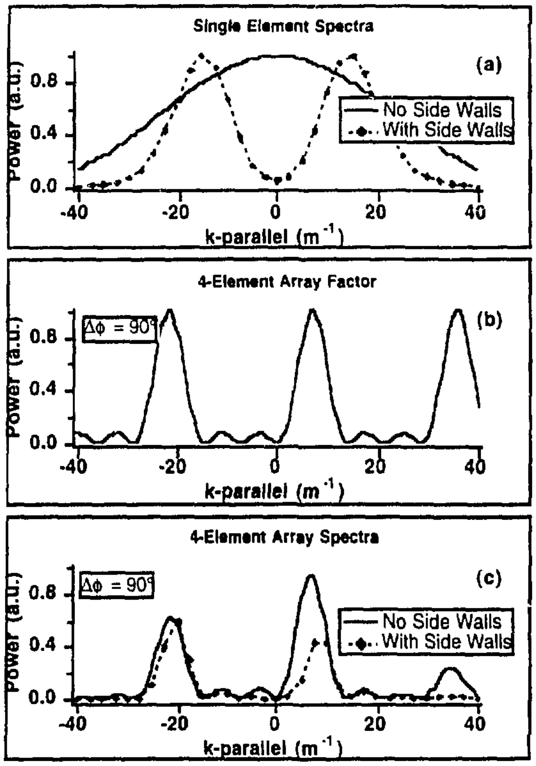

Fig. 2. (a) Single-element spectra for a bare current strap (calculated) and for a strap with side walls (measured on a DIII-D antenna mock-up). (b) The array factor for a four-element array. (c) The resulting spectra for the four-element array with and without side walls.

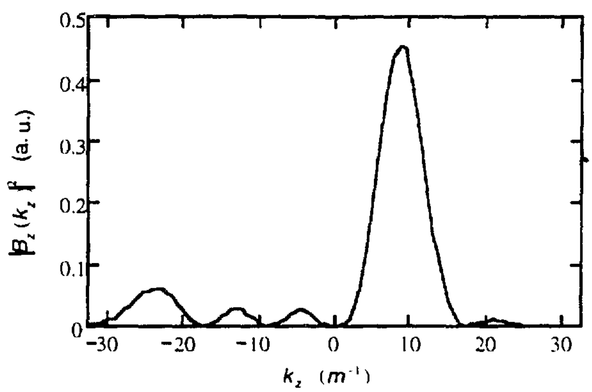

Fig. 3. The calculated toroidal power spectrum at the separatrix, using the DIII-D antenna geometry. The plasma parameters are representative of DIII-D (see [4]).

ARRAY CONTROL

There are significant differences between the feed circuits for the JET and DIII-D antenna arrays which are due mainly to the number of generators available to drive each element.. In the JET case (Fig. 4) each current strap is powered by a separate amplifier so that complete active control of phasing, and amplitude is possible. In the DIII-D system (Fig. 5) there is only one generator for the entire array, so that phase and amplitude can be controlled on a shot-to-shot basis only. In addition, in the DIII-D system, pairs of straps are connected by resonant loops to reduce the number of phasing and matching components required. The currents on the straps connected by a loop are locked into a relative phase of π for the resonant loop length shown in the figure.

Both systems use "decouplers" or "power compensators" to counteract the mutual impedances of the antennas. In the case of the DIII-D system, the resonant loops cause the antennas to look like a two port network to the feed circuit, which allows complete cancellation of the mutual impedances, using a decoupler which is just a transmission line with a stub mounted in parallel to control power flow. The location of the decoupler at a high impedance point in the feed lines is also advantageous in this case, as explained in [5].

The JET configuration allows almost arbitrary phasing, but the array acts as a true four-port network. A single decoupler can be used to counteract the net power transfer between the outer straps, but cannot completely cancel the array mutual impedances in general. The decoupler in this case is a quarter-wave coupler with adjustable capacitors to control the power flow. The location near the tuning stubs is advantageous for use over a wide range of frequencies with the voltage across the decoupler minimized.

In the JET system, feedback loops are used to control the phases and amplitudes of the antenna currents on a real time basis. Matching elements (single stub tuners with phase shifters) are also automatically controlled. In addition, the resistive loading can be controlled by plasma position feedback (a capability present on DIII-D as well), which reduces both the required movement of the tuning elements during a shot, and the frequency shift required for matching. A simplified schematic diagram of the JET rf control system is shown in Fig. 6. All of the error signals used for the control systems are obtained from directional coupler measurements of forward and reflected voltages made at just two locations on the inner lines, and three locations on the outer lines, as shown in the figure.

The frequency shift (Δf), phase shifters, and stubs are controlled by error signals formed from the real and imaginary parts of the ratio of voltages of the reflected waves on either side of the stubs (V_{ro}/V_{fm}), as has previously been the case on JET. The addition of the power compensator tee between the tuning stub and phase shifters does not interfere with this method of tuning control . The capacitors on the power compensator are controlled using the error signal $(P_{net4}-P_{net1})\times \mathrm{sign}(\phi_{v4}-\phi_{v1})$ where $P_{net1(4)}$ is the net power measured on the matched side of feed lines 1 (4), and $\phi_{v1(4)}$ is the phase of the voltage $V_c=V_{fc}+V_{rc}$.

The phase is controlled using the signal $\phi_c=1/2(\phi_{vf}+\phi_{vr})$, where ϕ_{vf} and ϕ_{vr} are the phases of the forward and reflected voltages respectively. On the inner lines these are measured on the load side of the tuning stubs (V_{fm}, V_{rm}), and on the outer lines on the load side of the tees connected to the decoupler (V_{fc}, V_{rc}). It can easily be shown that ϕ_c is equal to the phase of the voltage at a voltage maximum in the unmatched portion of line to within a factor of π. This eliminates the need to add a VSWR and frequency dependent correction to the phase which depends on the directional coupler location.

Another factor influencing phase control is that the JET antennas have been designed to operate over a wide range of

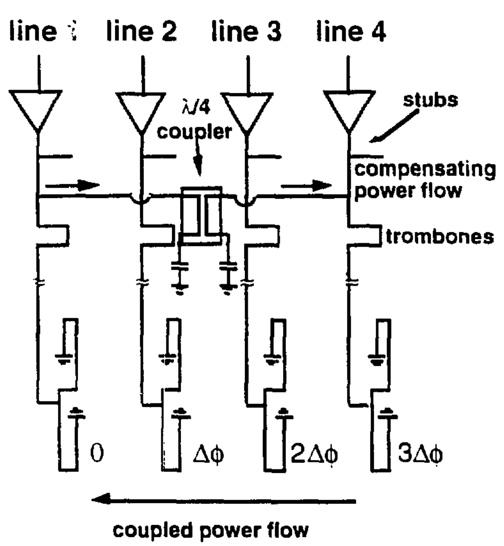

Fig. 4. JET feed circuit schematic.

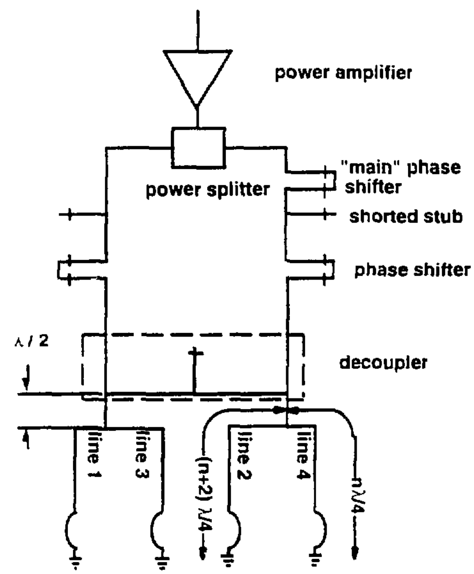

Fig. 5. DIII-D feed circuit schematic.

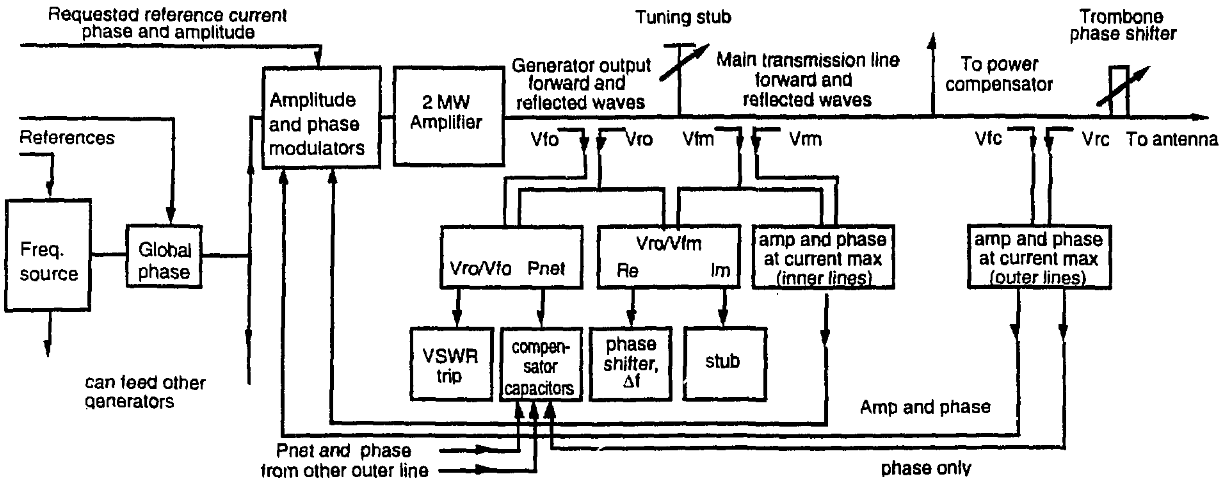

Fig. 6. The JET ICRF automatic control system for feed line 1.

frequencies (23-57 MHz), and have a resonant frequency at approximately 40 MHz. Because of this, the offset between ϕ_c and the phase of the maximum antenna current is a strong function of frequency, but more importantly, it is a function of the relative phasing between antennas, and is different for different elements. This is because the effective Q is different for different antenna elements, as a result of the power coupled between elements, which is a function of the relative phase. A lookup table can be inserted into the phase control circuitry to compensate for this effect.

Finally, the current amplitudes on the lines are also controlled using a position independent signal, which is the sum of the amplitudes of the forward and reflected voltages ($|V_{fm}|+|V_{rm}|$ for the inner lines, and $|V_{fc}|+|V_{rc}|$ for the outer lines).

TIME DEPENDENT MODELING

A collaborative effort between JET and ORNL is developing a time dependent model of the entire JET ICRF system, including all of the automatic feedback systems, the antenna array, and the plasma. A graphically based model of the control system has been created using the commercially available SIMULINK package, which internally creates and numerically integrates the set of differential equations describing the system.

A coupled transmission line model has been developed for complex antenna modeling, for use with the SIMULINK package. It can be used for arbitrary antenna geometries, includes both capacitive and inductive coupling between elements, self coupling internal to a single element, and allows for lumped impedances at arbitrary locations as well. The code produces explicit solutions relating currents and voltages at opposite ends of coupled sections, and automatically creates an array of coefficients which can be used to solve for currents and voltages at the ends of an arbitrary number of antenna sections.

Initial use of the time-dependent model has begun, and has to-date proven very useful in the development of the phase control portion of the control system. A final version will be installed in the JET control room, and used to suggest initial settings for the various control parameters.

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