SPECTRAL SHAPING AND PHASE CONTROL OF A FAST-WAVE CURRENT DRIVE ANTENNA ARRAY*

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ABSTRACT

The requirements for antenna design and phase control circuitry for a fast-wave current drive (FWCD) array operating in the ion cyclotron range of frequencies are considered. The design of a phase control system that can operate at arbitrary phasing over a wide range of plasma-loading and strap-coupling values is presented for a four-loop antenna array, prototypical of an array planned for the DIII-D tokamak (General Atomics, San Diego, California).

The goal is to maximize the power launched with the proper polarization for current drive while maintaining external control of phase. Since it is desirable to demonstrate the feasibility of FWCD prior to ITER, a four-strap array has been designed for DIII-D to operate with the existing 2-MW transmitter at 60 MHz.

SPECTRAL SHAPING

The spectrum launched by an array of side-by-side loop antennas depends on the dimensions, number, and spacing of the loops; the mutual coupling between loops; the relative phasing between loops; and the ratios of currents in each loop. The geometry of the loops is driven by considerations of maximizing the magnetic flux linked to the plasma, independent of any concern for driving plasma current. The number of loops will be controlled by the available space inside the tokamak. The mutual coupling between loops can be varied by the use of slotted septa between loops.

The spectra produced both with and without solid septa between loops are compared in Fig. 1 for the geometry of the DIII-D four-loop array. The calculation was based on equal currents in all loops and 90° phasing between loops. With no septa between loops, approximately 81% of the power is launched with $k_{\parallel}$ in the current drive peak; with full septa, only about 48% of the power is launched in the current drive peak. The effect of the plasma absorption on the spectrum was not taken into account. This must be done for calculations of the current drive efficiency.¹

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IMPEDANCE MATCHING CIRCUIT

For the DIII-D demonstration all four loops are driven from a single transmitter, but the circuit described here applies to any array with a pair of loops fed from the same rf source. For optimum spectral control it is necessary to have equal current magnitudes on each loop. Likewise, arbitrary phasing between loops is required for optimal $k_{\parallel}$ shaping. A practical system will also be stable over a range of plasma-loading resistance with high coupling between loops ($KQ \geq 1$, where K is the coupling factor between loops).

A schematic drawing of the circuit is shown in Fig. 2. The loops forming the array are fed in pairs by unmatched tees. Each loop is prematched by a single stub tuner to obtain the value of the input admittances at the tee that, for a given value of plasma loading, results in equal currents in each array element and produces an impedance match at the inputs to the tee. The phase between loops of each pair is controlled by an additional phase shifter in one leg of the tee.

With a coupled, lossy transmission line model, it can be shown² that, for the four-element array with currents that are equal in amplitude but not in phase, to a good approximation the real parts of the current strap input impedances scale as follows:

$$\text{Re}(Z_{in1}) \propto R - K_1 \omega L \sin \theta$$

$$\text{Re}(Z_{in2}) \propto R + (K_1 - K_2) \omega L \sin \theta$$

$$\text{Re}(Z_{in3}) \propto R - (K_1 - K_2) \omega L \sin \theta$$

$$\text{Re}(Z_{in4}) \propto R + K_1 \omega L \sin \theta$$

where R is the resistance per unit length; L is the inductance per unit length, K_1 is the coupling constant (ratio of M/L , where M is the mutual inductance per unit length) between loops 1 and 2 and between loops 3 and 4; K_2 is the coupling constant between loops 2 and 3; and θ is the (equal) phasing between neighboring loops. The small coupling between nonadjacent loops was ignored. If the currents into both elements in a pair are balanced, equal powers into the two tees will produce equal currents in all loops. In addition, this relation will hold independently of the relative phase and of the values of K_1 and K_2 . Thus, pairing elements 1 and 4 together and elements 2 and 3 together appears to be the most favorable of the possible choices for a parallel feed arrangement.

The transmission line parameters for the DIII-D current drive antenna design were calculated by using a 2-D magnetostatic code³, and the mutual inductances were measured on a small antenna array having a geometry similar to the DIII-D design. The strap length in the calculations was taken to be 0.4 m. Figure 3 shows the results of a calculation in which the resistance per unit length of the strap is varied, simulating changes in resistive plasma loading. The calculations were done for a frequency of 60 MHz, and the tuning element lengths were chosen to obtain equal currents and 90° phase

difference between straps for 6- Ω /m resistive loading. The current amplitude ratios remain constant for a wide range of loading values, although the phasing of the currents changes. Changing the length of the lines in legs 1 and 3 between the tees and the tuning stubs can alter the behavior of the circuit so that the phasing is stable except for very low loading values to changes in resistive loading, whereas the amplitudes are not stable (see Fig. 4).

In comparison, Fig. 5 shows the situation in which the input impedance of each array element is matched individually to 50 Ω (for 6- Ω /m loading) at the generator side of the single stub tuner. The forward power in all four legs is chosen to be the same for this case, as it would be if hybrid splitters were used to divide the power between legs. Note that the current ratios are far from unity, producing a significant degradation in the directionality of the $k_{||}$ spectrum produced. Of equal importance is the fact that, with the same amount of power applied, peak voltages are significantly higher for this case than for the equal-current case. This is due to unequal voltages on the straps, which correspond to the unequal currents, with some lines having higher voltages and some lower voltages than is the case with equal currents. The result is shown in Fig. 6, which shows the maximum voltage encountered in the four lines between the stub tuners and the array elements as the load varies for the cases of equal forward power and equal currents. For 2-MW input power and 4- Ω /m resistive loading, the peak voltage for the case of equal forward power is 10 kV higher than seen in the equal-current case. This difference could be critical if it were necessary to operate with only light loading.

CONCLUSIONS

In general, spectral shaping is improved by increasing the coupling between antennas, but phase control becomes more difficult. With the phase control system previously described, it is possible to operate at arbitrary phasing between antennas at coupling values considerably above critical coupling. These features allow both the power-handling capability of the antenna array and the $k_{||}$ spectrum generated to be optimized to the fullest extent possible.

REFERENCES

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Fig. 1. Calculated power spectrum launched by a 1-m-wide four-loop antenna array both with and without septa between loops.

Fig. 2. Schematic drawing of the tuning circuit for the DIII-D four-loop fast-wave current drive array.

Fig. 3. Calculated current ratios (a) and relative loop phase differences (b) as a function of plasma-loading resistance at 60 MHz, where the system was initially adjusted for 90° relative phasing and 6-Ω/m loading.

Fig. 4. Calculated current ratios (a) and relative loop phase differences (b) as in Fig. 3, except that the tuning was optimized for phase stability under load changes.

Fig. 5. Calculated current ratios for equal input powers to all loops for 90° phasing and 6 Ω/m at 60 MHz.

Fig. 6. The maximum voltages appearing on the antenna array for 2 MW input power for the case with equal currents compared with the case with equal powers on all loops.