GA-A21498

EXPERIMENTAL TEST OF A TWO-PORT DECOUPLER IN THE DIII-D FAST WAVE CURRENT DRIVE SYSTEM

by

R.I. PINSKER, F.W. BAITY, W.P. CARY,
R.H. GOULDING, C.C. PETTY

NOVEMBER 1993

GENERAL ATOMICS

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

GA-A21498

EXPERIMENTAL TEST OF A TWO-PORT DECOUPLER IN THE DIII-D FAST WAVE CURRENT DRIVE SYSTEM

by

R.I. PINSKER, F.W. BAITY,[†] W.P. CARY,
R.H. GOULDING,[†] C.C. PETTY

This is a preprint of a paper to be presented at the
15th IEEE/NPSS Symposium on Fusion Engineering,
October 11–15, 1993, in Hyannis, Massachusetts, and
to be printed in the *Proceedings*.

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

[†] Oak Ridge National Laboratory

GENERAL ATOMICS PROJECT 3466
NOVEMBER 1993

EXPERIMENTAL TEST OF A TWO-PORT DECOUPLER IN THE DIII-D FAST WAVE CURRENT DRIVE SYSTEM

R.I. Pinsker, C.C. Petty, W.P. Cary

General Atomics

P.O. Box 85608, San Diego, California 92186-9784

F.W. Baity and R.H. Goulding

Oak Ridge National Laboratory

P.O. Box 2009, Oak Ridge, Tennessee 37831

ABSTRACT

The DIII-D Fast Wave Current Drive (FWCD) system employs a pair of resonant loops of transmission line to reduce the four element phased antenna array to a two-port system. The equivalent two-port can be characterized by a 2×2 admittance matrix Y_{ij} , the off-diagonal elements of which are non-zero due to the reactive coupling between the elements in the antenna array. By connecting another two-port network (a "decoupler") in parallel with the two feedlines, it is possible to reduce the off-diagonal elements of the admittance matrix describing the resulting two-port device to zero, thereby effectively producing a system with no coupling between the two feedlines. In this paper we report a comparison of the theoretically predicted and experimentally determined characteristics of a decoupler in a high power ICRF system.

INTRODUCTION

Phased arrays of low impedance antenna elements have been used for many years to launch electromagnetic waves into tokamak plasmas for heating and, more recently [1], for current drive. In the case of current drive, the elements are typically phased at 90° to launch waves predominantly in one toroidal direction. The strong mutual reactance between elements in such arrays creates severe difficulties in impedance matching and phase control in 90° phasing. The methods used to surmount these difficulties in the DIII-D Fast Wave Current Drive (FWCD) system, where an array of four loops is phased at 90° with equal loop currents with a single 60 MHz transmitter, have been described in some detail [2,3].

The power division and phase control technique formerly used on DIII-D can be briefly summarized as follows. Alternate loops are maintained at 180° phasing by use of two resonant loops of transmission line, which are fed at a high impedance point. The use of this "1-3,2-4" feed scheme reduces the four-port antenna effectively to a two-port. The required 90° phasing between the two resonant loop feed points is produced by adjusting a line stretcher in one of the two feedlines, which are fed from an unmatched tee power splitter at the transmitter output. It is necessary to unbalance the net power in the

two feedlines to produce equal voltages at the resonant loop feed points in 90° phasing, due to the strong mutual reactance, as may be seen from the following expression for the input impedance looking into the two resonant loop feed points, labelled A and B :

$$Z_A^{in} = V_A / I_A = R_A + j\omega L_A + j\omega M_{AB}(I_B / I_A)$$

$$Z_B^{in} = V_B / I_B = R_B + j\omega L_B + j\omega M_{AB}(I_A / I_B)$$

Since the power flow into feed point A is $P_A = (1/2)\text{Re}(Z_A^{in})|I_A|^2$, and similarly for B , if $I_B / I_A = j$ (quadrature phasing with equal amplitudes), then the power split is

$$P_A / P_B = \text{Re}(Z_A^{in}) / \text{Re}(Z_B^{in}) = \frac{R - \omega M_{AB}}{R + \omega M_{AB}}$$

For the DIII-D system, typically $|R| \sim |\omega M_{AB}| \sim 1.5 \Omega$. The substantial power imbalance required to produce equal voltages at the resonant loops can be had only at the cost of a high standing wave ratio in one of the two feedlines, which in turn makes phase control problematic if the line stretcher is located in the high VSWR line. Also, conventional arc protection based on a maximum VSWR threshold is unusable in that line. Nevertheless, up to 1.2 MW in 90° phasing has been coupled to the plasma with this arrangement [3] under conditions such that the required power imbalance was about 3:1.

An alternative solution to the problems posed by strong mutual reactance in the antenna is the use of a "decoupler". This device, pioneered on the Phaedrus-T tokamak [4], consists of a reciprocal, lossless two-port with an adjustable cross-admittance Y_{12}^D . By connecting the decoupler in parallel with the two-port load, characterized by an admittance matrix Y^L , and adjusting the decoupler cross admittance so that the power reactively coupled from one port to the other within the load flows in the opposite direction through the decoupler, the mutual reactance of the load is effectively cancelled out (Fig. 1). That is, under decoupled conditions, the matrix Y^{tot} describing the two-port composed of the parallel connection of the load and the decoupler satisfies $Y_{12}^{tot} = Y_{21}^{tot} = 0$, so that the transmission coefficient from

FIG. 1. Power flow with two port load and decoupler adjusted so that $P/2 = P_A + P_D$ and $P/2 = P_B - P_D$. If $P_A \neq P_B$, as would be the case with a nonzero mutual reactance in the load and the phase difference between V_A and V_B , denoted as $\Delta\phi$, not equal to 0° or 180° , then $P_D \neq 0$.

one port to the other vanishes. Impedance matching of the two input lines then proceeds as though the two lines were connected to separate, uncoupled loads.

In general, the adjustment of the decoupler will depend on the phase angle $\Delta\phi$ between the two voltages V_A and V_B , as well as on Y_{11}^L and Y_{22}^L . The net power flow through the decoupler is given [5] by $P_D = (1/2)|V_A||V_B|\sin(\Delta\phi)\text{Im}(Y_{12}^D)$. However, in the special case that the two points are at equal voltage ($|V_A| = |V_B|$) and the load is symmetric and reciprocal so that $\text{Re}(Y_{11}^L) = \text{Re}(Y_{22}^L)$ and $\text{Re}(Y_{12}^L) = \text{Re}(Y_{21}^L)$, the condition for decoupling becomes $\sin(\Delta\phi)\text{Im}(Y_{12}^D) = -\sin(\Delta\phi)\text{Im}(Y_{12}^L)$. This is either trivially satisfied at $\Delta\phi = 0$ or π , when there is no power flow through the decoupler or if $\text{Im}(Y_{12}^D) = -\text{Im}(Y_{12}^L)$. If the latter condition is satisfied, decoupling is achieved at arbitrary phase angle.

In the situation of the "1-3,2-4" feed scheme with resonant loops, the voltage magnitudes at the two resonant loop feed points must be equal to obtain equal antenna currents, as discussed above. By connecting the decoupler between the two resonant loop feed points, phase-independent decoupling can be obtained. Furthermore, since the resonant loop feed points are at voltage maxima (purely real input impedance) at any value of the antenna load resistance, the decoupler adjustment will be independent of the resistive component of the antenna load.

The properties of a decoupler can be satisfied by many different configurations of lumped or distributed adjustable reactances. The version of the decoupler chosen for this test is based on a standard stripline 3 dB hybrid junction with two of its four ports terminated in adjustable reactances. This decoupler configuration was apparently first suggested in Ref. [6]; its application to the DIII-D FWCD system is illustrated in Fig. 2. The symmetry of the system with respect to interchange of "A" and "B" can be preserved by adjusting the two terminating reactances to be always equal.

A system incorporating the decoupler connected at the resonant loop tees has several potential advantages

FIG. 2. Application of the 3 dB hybrid decoupler to the DIII-D FWCD system with resonant loops. Another 3 dB hybrid is used to split the transmitter power equally to feed the two sides of the system, denoted "A" and "B". The matching network in each line consists of a line stretcher and a stub tuner in series.

over the previous FWCD system described in Refs. [2,3]. These may be summarized as follows. (1) The tuning algorithm is greatly simplified, as each of the two feedlines is matched to 50Ω , instead of the rather complicated and asymmetric system of partial mismatches necessary without the decoupler. To change antenna phasing, only one phase shifter is adjusted, and the remainder of the matching network is unchanged. (2) The standing wave ratio in both lines between the matching network and the generator is unity at all phases, minimizing rf dissipation and the probability of breakdown in these long lengths of coax. (3) The decoupler allows the use of a 3 dB hybrid junction as the power splitter at the antenna, providing a greater degree of isolation for the output stage of the transmitter than the simple tee power splitter used in the previous system. (4) If the decoupler is designed so that it does not introduce significant self-reactance to the feedlines at the points where it is connected, the symmetry of the system yields a purely real impedance looking into the resonant loop feed points at any phase angle, so that quarter wave transformers may be used effectively to minimize the VSWR in the length of line between the matching network and the resonant loops, thereby minimizing the stress on the tuning elements. (5) Conventional over-VSWR arc detection can be used in the two feed lines as well as an additional sensor based on monitoring abrupt changes in the net power flow through the decoupler.

Given these potential advantages of the decoupler-based system, an experimental evaluation of such a system was performed. The goal of the test described in the remainder of this paper was to demonstrate the

practicality of a decoupler at the 0.1 MW power level in the DIII-D FWCD system. The decoupler was to be constructed using available standard coaxial components. The decoupler stub settings were to remain fixed during a plasma discharge. A successful test would justify an effort to design and fabricate a permanent decoupler suitable for full power operation (2 MW).

CONSTRUCTION & CALIBRATION OF THE DECOUPLER

The decoupler was built around an existing 3 dB hybrid junction with 3-in. coaxial feeds. The length of the coupled lines in the hybrid junction was 122 cm, so that the center frequency of the the hybrid was at 61 MHz. The pair of adjustable reactances with which two of the four ports of the hybrid were terminated consisted of motorized stub tuners built in 3-in. 50 Ω coaxial line. These stubs were loaned to DIII-D by the Princeton Plasma Physics Laboratory, along with other coaxial components necessary for this test. Prior to final assembly and installation of the decoupler, the electrical lengths of all of the components and the coupling coefficient of the hybrid junction were measured with a network analyzer. Measurements made of the scattering parameters of various subsets of the complete decoupler assembly were found to be in excellent agreement with modelling.

After connection of the resonant loop feed points to the decoupler assembly, the scattering matrix elements of the two-port consisting of the antennas, resonant loops, and decoupler were measured over the 50–70 MHz band with the antennas in vacuum at several decoupler stub positions. In particular, the effective mutual inductance seen between the resonant loop feed points was determined by adjusting the decoupler stubs so that (1) the transmission coefficient between the two ports vanished at 59.5 MHz (the resonant frequency of the loops with the antennas in vacuum) and (2) the two reflection coefficients looking into each port with the other terminated in 50 Ω were equal at all frequencies (symmetry condition). The value of $M = 9$ nH obtained by comparison of the measured transmission coefficient phase with the model is in good agreement with the value expected based on measurement of the individual mutual couplings between the antenna elements in vacuum. Figure 3 shows the comparison of the measured and predicted transmission coefficient amplitude and phase.

Having thus determined the appropriate symmetric settings of the decoupler stubs to achieve decoupling at 59.5 MHz with the antennas in vacuum, the magnitude of the ratio between the voltages at the resonant loop feed points should be unity independent of the phase between the two voltages, given equal input power to the two feed points. Maintaining the symmetry of the system implies that the impedance matching network should not require adjustment as a function of phase. These expectations were born out by measurements performed at the 100 W level using a network analyzer and an amplifier. The voltages at the resonant loop feed points were monitored

FIG. 3. Comparison of theoretical and measured transmission coefficient S_{12} with decoupling at 59.5 MHz, unloaded antennas. The stub position required to achieve decoupling indicates that the effective mutual inductance is $M = 9$ nH.

with capacitively coupled probes built into the resonant loop tees. The matching network was adjusted so that the reflection coefficient on the generator side vanished at a particular phasing. The phase shifter near the generator was then moved over its range (360° at 60 MHz) while monitoring the resonant loop tee voltages and the reflection coefficient on the generator side without any further adjustment of the decoupler or of the matching network. The variation of the ratio of the resonant loop tee voltages was less than about 10% over the 360° range, under conditions where $R_L \sim 0.1 \Omega$ and $\omega M \sim 3 \Omega$. The tuned side reflection coefficients rose to maxima of $|\rho_A| \sim 0.15$, $|\rho_B| \sim 0.09$ over the phase range.

ADJUSTMENT AND OPERATION OF THE DECOUPLER WITH PLASMA LOAD

The most straightforward method of obtaining the appropriate decoupler setting with plasma-loaded antennas would be to measure the transmission coefficient between the two input ports during a tokamak discharge and adjusting the decoupler to achieve zero transmission while maintaining symmetry. Though a series of measurements of this kind were carried out with a network analyzer, such detailed measurements proved to be unnecessary to obtain satisfactory performance of the decoupler. Model calculations indicated that the setting of the decoupler was not very critical with reasonable resistive loading of the antennas. In any case, load resistance of about an Ohm or more is necessary to keep the voltages in the resonant loops below ~ 30 kV at the full power of 2 MW, independent of the mutual reactance. Therefore the following procedure was used to adjust the decoupler.

The antenna load resistance was kept constant at $1.5\ \Omega$ by controlling the plasma radial position and hence the plasma/antenna gap with the DIII-D digital control system [7]. The starting positions of the decoupler stubs were appropriate for decoupling in vacuum. The phase was set at $\Delta\phi = 90^\circ$, as measured at the resonant loop feed points. The magnitude of the voltage ratio $|V_B|/|V_A|$ there was found to decrease from unity in vacuum to 0.71 with a plasma load. On the next two tokamak discharges, the stubs were successively reduced in electrical length in 8 mm increments and $|V_B|/|V_A|$ rose to 0.87 and finally to 1.01. The set of stub positions thus arrived at was appropriate to an effective mutual inductance of 5 nH. The nearly factor-of-two decrease of the mutual from the vacuum value is consistent with the measurements reported in Ref. [3]. That these settings were correct was verified by changing the phase to $\Delta\phi = -90^\circ$, without adjustment of the matching network: $|V_B|/|V_A|$ remained equal to 1 and the reflection coefficient on the generator side of the matching network was unchanged. Satisfactory adjustment of the decoupler was thus achieved after about three tokamak discharges.

On the next fourteen discharges, the phase of V_B/V_A was varied over the full 360° range, with the decoupler stubs and the matching network left fixed and the forward power fixed at 0.1 MW. Fig. 4 shows the measured magnitude and phase of V_B/V_A from this series along with the vector reflection coefficients ρ_A and ρ_B from the generator side of the matching network. Also shown is the ratio of the forward voltages $|V_B^f|/|V_A^f|$ from the generator side. The slight imbalance in the forward power is a result of operating the power splitting hybrid junction at a frequency different from an exact 3 dB point.

CONCLUSION

The application of the decoupler to the DIII-D FWCD system has proven to be an unqualified success. The shot-to-shot variations of the mutual reactance and the fluctuations in this quantity during a discharge have not presented a problem, as long as the resistive load exceeds about an Ohm ($\omega M/R < 2$). In vacuum, operation at $\omega M/R$ in excess of 30 has been achieved. This has permitted vacuum conditioning of the system with equal antenna currents at 90° phasing, which is clearly an impossibility without a decoupler. Adjustment of the decoupler to plasma loading was remarkably simple and quick, due to the lower Q of the system when the antennas are loaded. Even with 3-in. coaxial components, power levels of 0.25 MW in directional phasing were easily reached without breakdown in the decoupler.

The successor to this proof-of-principle experiment was a decoupler of a different design, capable of withstanding 2 MW, 2 s long rf pulses without breakdown or overheating. The results from the new decoupler have been equally positive, and the device has become an essential part of the present 2 MW FWCD system on

FIG. 4. Measured ratio of the voltages at the two resonant loop feed points V_B/V_A (filled circles), the ratio of the forward voltages on the generator side of the matching network V_B^f/V_A^f (open circles), and the vector reflection coefficients on the generator side ρ_A (crosses) and ρ_B (diamonds) from a series of discharges with the decoupler and matching network fixed. The antenna load resistance was $R_L = 1.5\ \Omega$ and the forward power was 0.1 MW.

DIII-D. Lack of space precludes a discussion of these results in this paper. Further refinement of the decoupler has been incorporated into the new 4 MW 30–120 MHz FWCD system, as is described in Ref. [8].

REFERENCES

- [1] R.I. Pinaker, C.C. Petty, M. Porkolab, et al., in *Plasma Phys. and Contr. Nucl. Fusion Research 1992* (Würzburg, September 30–October 7, 1992), (IAEA, Vienna, 1993) vol. I, p. 683.
- [2] R.I. Pinaker, M.J. Mayberry, C.C. Petty, et al., in *Proc. 14th IEEE/NPSS Symp. on Fusion Engineering*, San Diego, California 1991 (IEEE, Piscataway, NJ, 1992) vol. I, p. 115.
- [3] R.H. Goulding, F.W. Baity, D.J. Hoffman, et al., "Phased Operation of the DIII-D FWCD Antenna Array with a Single Power Source," to be published in *Fusion Engineering and Design*.
- [4] N. Hershkowitz, R. Majeski, P.H. Probert, et al., *Radio Frequency Power in Plasmas: 9th Topical Conf.*, Charleston, South Carolina 1991 (American Institute of Physics, New York, 1992), p. 267. to be published in *Fusion Engineering and Design*.
- [5] R.H. Goulding, et al., *Radio Frequency Power in Plasmas: 10th Topical Conf.*, Boston, Massachusetts 1993 (American Institute of Physics, New York, 1993).
- [6] G. Bosia and J. Jacquinot, in *Proc. IAEA Tech. Comm. Meeting on Fast Wave Current Drive in Reactor Scale Tokamaks*, Arles, France, 1991 (Association EURATOM-CEA, Cedex, France, 1992), p. 471.
- [7] G.L. Campbell, J.R. Ferron, E. McKee, et al., in *Proc. 17th Symp. on Fusion Tech.*, Rome, Italy, 1992 (Elsevier, The Netherlands, 1993), vol. II, p. 1017.
- [8] J.S. deGrassie, R.I. Pinaker, W.P. Cary, et al., these proceedings.

END

DATE

FILMED

11/11/94