4 MW UPGRADE TO THE DIII-D FAST WAVE CURRENT DRIVE SYSTEM

by

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ABSTRACT

The DIII-D fast wave current drive (FWCD) system is being upgraded by an additional 4 MW in the 30 to 120 MHz frequency range. This capability adds to the existing 2 MW 30 to 60 MHz system. Two new ABB transmitters of the type that are in use on the ASDEX-Upgrade tokamak in Garching will be used to drive two new water-cooled four-strap antennas to be installed in DIII-D in early 1994. The transmission and tuning system for each antenna will be similar to that now in use for the first 2 MW system on DIII-D, but with some significant improvements. One improvement consists of adding a decoupler element to counter the mutual coupling between the antenna straps which results in large imbalances in the power to a strap for the usual current drive intrastap phasing of 90° . Another improvement is to utilize pressurized, ceramic-insulated transmission lines. The intrastap phasing will again be controlled in pairs, with a pair of straps coupled in a resonant loop configuration, locking their phase difference at either 0 or 180° , depending upon the length of line installed. These resonant loops will incorporate a phase shifter so that they will be able to be tuned to resonance at several frequencies in the operating band of the transmitter. With the frequency change capability of the ABB generators, the FWCD frequency will thus be selectable on a shot-to-shot basis, from this preselected set of frequencies. The schedule is for experiments to begin with this added 4 MW capability in mid-1994. The details of the system are described.

INTRODUCTION

The Fast Wave Current Drive (FWCD) program on the DIII-D tokamak is a collaborative effort between General Atomics (GA) and the Oak Ridge National Laboratory (ORNL), with ORNL providing the design and fabrication of the FWCD antennas [1] and GA providing the technology to generate, transmit, and couple the high power rf to the antenna as well as perform the physics experiments. This paper describes the upgrade of the DIII-D high power rf system from the present 2 MW capability, at 30 to 60 MHz, by an additional 4 MW, at 30

to 120 MHz. The upgrade is scheduled for completion by mid-1994 with physics experiments to begin immediately thereafter.

FWCD experiments on DIII-D with the existing 2 MW system have achieved over 100 kA of rf current drive, with up to 40% of the plasma current driven noninductively [2] in the 1991 campaigns, and recently driving up to 70% of the plasma current noninductively. These levels of current drive are consistent with theoretical predictions for the experimental parameters. Theory and modeling predict greater current drive efficiency for DIII-D at higher frequency [3], leading to the choice of generators with a higher frequency capability for the upgrade.

On DIII-D each generator will drive one antenna module consisting of four straps [1,4], which must be phased consecutively by 90° to launch the toroidally-directed spectrum for current drive. The mutual inductance between straps makes the tuning and matching of a single generator difficult, but successful techniques have been developed on the present system [5]. The upgrade will utilize this same basic transmission line topology, with some significant improvements, as described below.

An overall schematic of one of the two new generator/antenna systems is shown in Fig. 1. The two systems will be essentially identical. We describe the generator and transmission system in the next two sections, respectively.

RF GENERATOR

The high power rf generators are being supplied by THOMCAST AG, formerly Asea Brown Boveri Infocom (ABB). These generators are of the same type in service on the ASDEX Upgrade experiment at the Max-Planck Institute for Plasma Physics [6]. The maximum output power of the rf generator depends upon the operating frequency and the VSWR presented by the load and transmission system at the output of the final stage of the

FIG. 1. Schematic of one of two identical systems for the DIII-D 4 MW Fast Wave Current Drive upgrade.

generator. Fig. 2 displays the maximum power output profile. Full power pulse length is limited to 20 sec, with a maximum duty cycle of 10%. The average power limitation is due to the power supplies selected rather than the rf generators. The instantaneous bandwidth, at 1 dB degradation, is $\pm 0.25\%$.

The generator consists of four stages of rf amplification, the first a stand-alone solid state rf amplifier, followed by three tube stages. Nominal full-power output levels for each stage are 50 W, 5 kW, 100 kW, and 2 MW, respectively. The final stage is of a symmetrical coaxial design utilizing an ABB-type CQK 650-2 tetrode. All tuning elements between stages are motorized and are interfaced to the transmitter digital control system,

FIG. 2. Output power profile for new DIII-D transmitters.

allowing the operating frequency to be changed, between DIII-D discharges, on a ten minute timescale, to any one of 12 preset frequencies within the 30 to 120 MHz operating band. The ability to change frequency on a relatively short timescale is important for the physics understanding of FWCD and has therefore also driven the design philosophy for the resonant elements in the transmission system described in the next section.

TRANSMISSION AND TUNING SYSTEM

To understand the design of the transmission system, we start at the antenna straps and work back toward the generator (see Fig. 1). The antenna straps are "folded" [1] to minimize the length of a single poloidal section relative to the rf wavelength along the section. Each strap is modeled as a section of transmission line of impedance 25Ω with a total loading resistance R due to the power delivered to the plasma. This loading resistance depends upon the frequency and the details of the plasma parameters, and is expected to be in the range of 1 to 3Ω for typical conditions.

Current drive operation requires that a toroidally-directed spectrum be launched from the antenna. Viewing the four straps of one antenna as a phased array of radiators, the maximally directed spectrum is obtained by applying a 90° phase shift between adjacent straps, i.e., $\Phi_n = (n-1)\pi/2$, with the rf current in the four straps $I_n = I_0 \exp i(\omega t - \Phi_n)$, $n = 1, \dots, 4$. A resonant loop arrangement is used to lock the phase difference of

two straps at 180° [5], as indicated in Fig. 1. Consider straps (1) and (3) which are connected to a single node A. The connection consists of a length of vacuum coax, within the DIII-D vessel, a high vacuum rf feedthrough [1], and a length of pressurized 6-1/8 in. $25\ \Omega$ coax transmission line utilizing ceramic insulators. The total electrical length l from a vessel-shorted strap to A is an odd number of quarter wavelengths, with $l_3 - l_1 = \lambda/2$, where λ is this wavelength, so that $\Phi_3 - \Phi_1 = \pi$. The same arrangement is used on straps (4) and (2) with connection to node B, and a proper phase shift, Φ_{AB} ($3\pi/2$ in this case), between A and B brings the four straps to the desired current drive phasing.

On the existing DIII-D FWCD system, the resonant loops are of fixed lengths, so that a change in operating frequency requires a change in the mechanical lengths. The upgrade systems employ a line stretcher in one-half of each resonant loop to access a sequence of discrete frequencies by simply moving the stretcher. For example, at the highest operating frequency f_0 (120 MHz), take $l_2 = l_3 = (2k + 1)(\lambda_0/4)$, and $l_1 = l_4 = (2k - 1)(\lambda_0/4)$, where k is an integer. Lines (2) and (3) are of fixed length and lines (1) and (4) are variable. Lines (2) and (3) are also resonant for each $f_m = c/\lambda_m$, such that $l_2 = l_3 = (2k' + 1)(\lambda_m/4)$ with $k' = k - m$. Lines (1) and (4) are brought into resonance at these same frequencies by adjusting the lengths with the line stretchers such that $l'_1 = l'_4 = (2k' - 1)(\lambda_m/4)$. Additionally, the travel of these line stretchers is sufficient to make all lines of equal length, which can be used to launch symmetric antenna spectra with so called "dipole" or "monopole" phasing for plasma heating rather than current drive.

The resonant loops are relatively long, compared with the present DIII-D system, in order to locate the loop line stretchers and decoupler stubs outside of the DIII-D torus area. This obviates any loss of access to the DIII-D vessel due to the four 6-1/8 in. lines feeding the four antenna straps. For one system, the design calls for $k = 16$, while for the other $k = 22$. The maximum resonant frequency f_0 for the two systems will not be the same for both. Rather, it will differ by 0.5 to 1.0 MHz to minimize cross talk between the transmitters when operated near the same resonant frequency.

Each line of the resonant loop employs a dc break on the inner and outer conductors of the coax which serves to preclude possible induced currents driven by the air core Ohmic heating coil in DIII-D, and acts as a safety break for tokamak fault conditions which could potentially bring the DIII-D vacuum vessel to a high voltage. The rf insertion loss of a break is to be less than 0.05 dB, and the specified voltage holdoff capability is 30 kV continuous.

The quarter wave nature of the resonant loop lengths transforms the low antenna loading resistance on each strap to a high resistance at nodes A and B. Were it not for the mutual inductance between the straps,

matching the generator to these nodes would be straightforward, neglecting the dynamic nature of the plasma load. In current drive phasing the mutual coupling creates an imaginary cross admittance between A and B, Y_{AB}^{Ant} , which is a result of toroidally-directed power flow from one strap to another. Techniques to obtain a match have been developed [5]. However, recent tests on the existing DIII-D system have lead to the development of a simplified "decoupler" to recirculate this traveling power between A and B [7]. It is simply a shorted stub placed between A and B as shown in Fig. 1. The length of the stub must be adjustable to accommodate the frequency range. The decoupler stub, together with the joining lines from A and B, cancels Y_{AB}^{Ant} . That is, $Y_{AB}^{Ant} + Y_{AB}^{Decoupler} = 0$. However, the decoupler also introduces an imaginary $Y_{AA}^{Decoupler} = Y_{BB}^{Decoupler}$ at nodes A and B. The additional adjustable length shorted stubs located at A and B will be used to bring these nodes to a real impedance value as seen from the generator side to facilitate matching. These elements are in 9-3/16 in., $50\ \Omega$, ceramic-insulated, pressurized coax line, as are all of the components between A and B and the generator.

With proper settings of the decoupler stub and the two susceptance nulling stubs, nodes A and B are balanced, with a real impedance as seen from the generator side which is high relative to the $50\ \Omega$ generator and primary feed lines. Broadband transmission line transformers are used to reduce the VSWR in the main line-stretcher/stub-tuner sections. For example, a transformer line of total length 1.7 m consisting of two discrete sections of impedance 116 and $66\ \Omega$, respectively, can be used to keep the upstream VSWR below 2 for the anticipated antenna loading range, in the frequency band 60 to 120 MHz.

A critical component of the resonant loop and decoupler assembly is the five-way junction at nodes A and B. Three of the outer conductor flanges on the junction will mate to 9-3/16 in. flanges, while the other two mate to the 6-1/8 in. flanges of the resonant loops. The inner conductors within the junction (with the exception of that leading to the transmission line transformer) will be of constant diameter (4 in.), giving a $50\ \Omega$ impedance for the 9-3/16 in. outer conductor and $25.5\ \Omega$ impedance for the 6-1/8 in. outer conductor. A voltage probe will be mounted in the remaining "side" of the five-way junction.

The next element in the tuning and matching system is a standard line-stretcher/stub-tuner pair on both the A and B sides, which transforms the reflected impedance of the transformer sections into $50\ \Omega$. Each of these elements has a length variation capability of 180° at 54 MHz. Side B has the main phase shifter, in matched line, to set Φ_{AB} . With the decoupler, Φ_{AB} can be properly adjusted with the overall match maintained to lowest order. This phase shifter has a capability of a 360° variation at 54 MHz.

The remainder of the system is straightforward. The generator power is split into the A and B sides with a 3 dB hybrid junction, optimized for the primary 60 to 120 MHz band of operation. A four-port, two-way switch is used to direct any power reflected through the hybrid to a dummy load, or to direct the generator power directly to the dummy load. Additionally, for testing and calibration purposes, fixed sections of line can be installed to bypass the power divider and to circulate the power from A to B, so that the generator power can be directed through all of the 9-3/16 in. lines in a loop to the dummy load.

Both new systems will be controlled with a SUN SPARCstation 10 computer using VXI based data acquisition and control hardware [8]. Data from directional couplers, voltage, and current probes located throughout the system will be acquired during a shot. The computer will use this information to make any necessary changes in the positions of the line stretchers and stubs before the next shot. Some real time control functions are planned for generator protection and eventually for control of fast ferrite tuners [9].

The dummy loads are of the standard soda solution type and are colocated to share the same soda water tank. The continuous power rating for each is 100 kW and the peak power rating is 3 MW.

SUMMARY

The 4 MW FWCD upgrade system for DIII-D makes use of improvements motivated through experience with the existing 2 MW system. These include line stretchers in the resonant loops for ease of multiple frequency operation, a simple decoupler to recirculate the traveling power coupled by the mutual inductance between straps in current drive phasing, susceptance nulling stubs to obtain a real impedance at the resonant loop nodes, broadband transmission line transformers, and the use of pressurized transmission lines, stretchers and stubs with ceramic insulation. The generators will provide the potential for a broad range of accessible frequency. When coupled with the two new antennas we

anticipate that the addition of 4 MW to our existing capability will allow the demonstration of full noninductive current drive in enhanced confinement discharges near the 1 MA level [10].

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