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4 MW FAST WAVE CURRENT DRIVE UPGRADE FOR DIII–D

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4 MW Fast Wave Current Drive Upgrade for DIII–D*

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The DIII–D program has just completed a major addition to its ion cyclotron range of frequency (ICRF) systems. This upgrade project added two new fast wave current drive (FWCD) systems, with each system consisting of a 2 MW, 30 to 120 MHz transmitter, ceramic insulated transmission lines and tuner elements, and water-cooled four-strap antenna. With this addition of 4 MW of FWCD power to the original 2 MW, 30 to 60 MHz capability, experiments can be performed that will explore advanced tokamak plasma configurations by using the centrally localized current drive to effect current profile modifications.

1. INTRODUCTION

In the long range plans for the DIII–D experimental program, one of the primary objectives is to demonstrate the feasibility of using noninductive current drive to control the current density profiles in order to produce advanced tokamak configurations. For this purpose, the DIII–D program in 1992 initiated an upgrade of its Fast Wave Current Drive (FWCD) program to add an additional 4 MW of 30–120 MHz rf power [1].

The FWCD program on the DIII–D tokamak is a collaborative effort. Oak Ridge National Laboratory (ORNL) led the design and fabrication of the FWCD antennas [2]. General Atomics (GA) was responsible for the generation, transmission, and coupling of the high power rf to the antenna. The experimental activities are carried out with multi-institutional participation.

The 4 MW upgrade consists of two systems each having its own 2 MW transmitter connected to a four-strap antenna by an all-ceramic insulated coaxial transmission line. The transmission line is configured to provide the flexibility of adjusting the phasing of the straps for electron heating $(0,\pi,0,\pi)$ and for current drive phasing of $(0,\pi/2,\pi,3\pi/2)$, while providing matching between the antenna-plasma impedance ($\approx$1–4 Ω) and the 50 Ω impedance that the transmitter requires for optimum power delivery [3]. The matching system must also compensate for the mutual inductance between the straps, which has been achieved by using a decoupler concept [4] developed earlier for the original 2 MW DIII–D FWCD system.

An overall schematic of one of the two new transmitter/antenna systems is shown in Fig 1. Both systems are topologically the same, although the routing of the transmission line is different in order to comply with the DIII–D building layout. The transmitters, transmission lines and the four-strap antennas are described in more detail in the following sections.

2. TRANSMITTER

The high power rf transmitters are being supplied by THOMSCAST AG, formerly Asea Brown Boveri Infocom (ABB). These transmitters are of the same type as those in service on the ASDEX Upgrade experiment at the Max-Plank Institut für Plasma Physics [5]. The overall design of a 2 MW rf generator is shown in the block diagram (Fig. 2).

The transmitter consists of four stages of rf amplification: pre-amplifier, predriver, 100 kW high power

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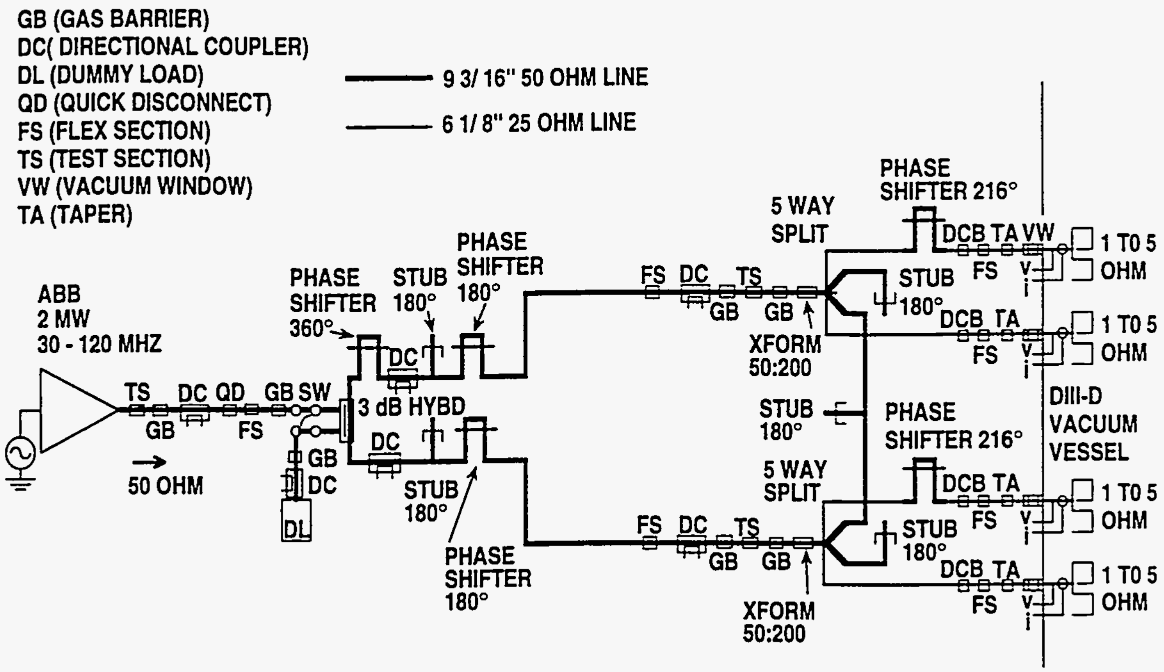

Fig. 1. Schematic for one of the 2 MW 30–120 MHz fast wave current drive systems.

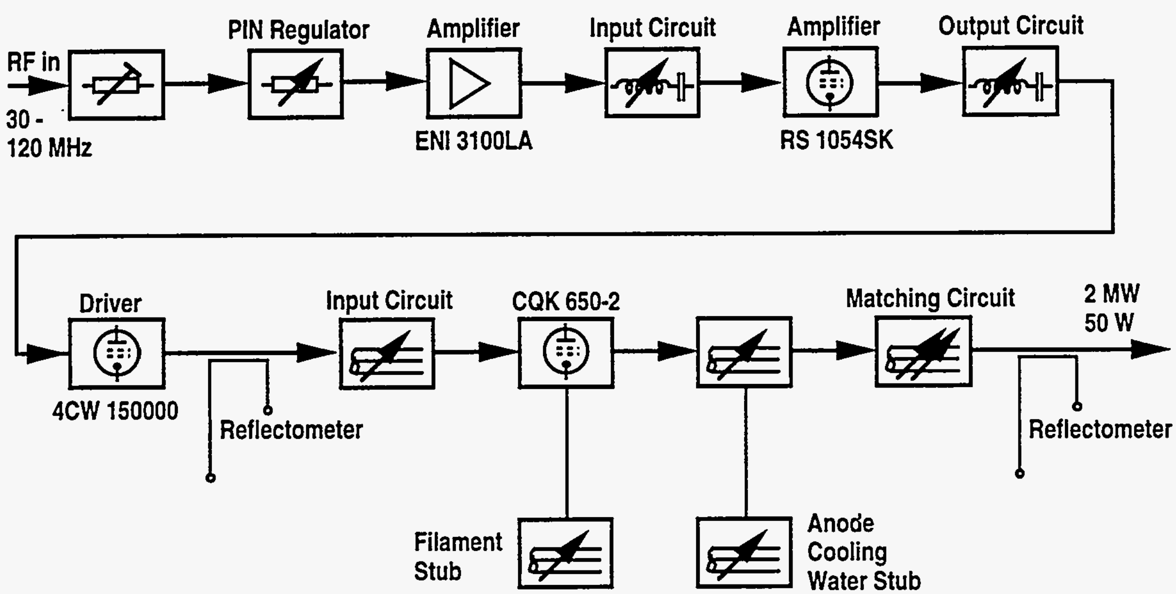

Fig. 2. Block diagram of the RF transmitter amplifier stages.

driver, and the 2 MW high power final. The input signal is fed to the 50 W rf preamplifier by way of an attenuator and the PIN regulator. The 5 kW predriver stage is of a straightforward design and uses a water-cooled Siemens type RS1054 transmitting tetrode. The input and output tuning circuits of this grounded-cathode stage are motor driven. The 100 kW high-power driver stage is a grounded-grid configuration using a type 4 CW 150000 tetrode made by Eimac. The output circuit is designed as a coaxial λ/4 circuit with a 50 Ω output impedance adjusted by a motor-driven variable coupling. The 2 MW high power final stage is entirely a coaxial design. It is fitted with an ABB type CQK 650-2 tube, operated in a grounded-grid configuration. The output circuit is made up of coaxial line sections with tuning achieved by motor-driven sliding elements. The control system can store the position of the tuning elements for up to 12 different frequencies, so that when the operator wants to change frequencies, a recall of the stored tuning element locations is all that is required. The specifications for the transmitter are given in Table I.

3. TRANSMISSION LINE

The experimental objectives of the fast wave program required a transmission line that could independently adjust the phasing of each strap of the four-strap antenna and be capable of reliable 1 MW/strap multi-second pulses. To achieve the latter, all transmission line components were specified with all-ceramic insulators and the capability of being pressurized to 3 atm. This specification was driven by the desire to have a voltage standoff capability of 70 kV and 50 kV rf peak for the 9-3/16- and 6-1/8-in. components respectively.

To achieve the phasing control, the topology shown in Fig. 1 was chosen. Alternate straps of the antenna are maintained at 180° phasing by use of two resonant loops of 6-1/8-in. transmission line, which are fed at a high impedance point. The resonant loop arrangement is used to lock the phase difference between two of the four straps of the antenna. The phase shifter in this loop has sufficient travel to equalize both sides of the loop. This allows the antenna straps to launch symmetrical spectra. To obtain directed spectra for current drive, the phase shifter of each of the loops is adjusted to create a half wavelength difference in the two sides of the loop. This phase shifter, even though it is in the 6-1/8 diameter coax line, is 9-3/16, 25 Ohms, providing better voltage handling capability.

Table 1
Specification of the ABB Type VU 62 B transmitter

Frequency range	30 MHz to 120 MHz
Bandwidth	±0.25%–1 dB; ±75 to ±300 kHz – 1 dB
Output power	From 30 MHz to 80 MHz, 2.0 MW At 100 MHz, 1.5 MW At 120 MHz, 1.0 MW Into 50 Ohms, VSWR 1:1.5
Pulse duration	20 s maximum
Duty cycle	10% maximum

In the situation of the "1-3, 2-4" feed scheme with resonant loops, the voltage magnitudes at the two resonant loops feed points must be equal to obtain equal antenna currents. By connecting a decoupler between the two resonant loop feed points, phase-independent decoupling can be obtained. The connection of a decoupler at each feed point creates a 5-way connection point.

Each 5-way "cross" has three 9-3/16 in. diameter ports and two 6-1/8 in. ports. The inner conductor of the cross is 4 in. on all ports except for the transformer section, allowing 50 Ohm impedance for the 9-3/16 in. diameter ports and 25 Ohm impedance for the 6-1/8 in. ports. A voltage probe has been installed on the sixth side of the 5-way cross cube for diagnostic measurements. Each of the 6-1/8 in. diameter, 25 Ohm transmission lines connects to a strap of the antenna inside DIII–D. In current drive phasing, the mutual inductance between the straps creates a transconductance between the 5-way crosses [4]. To decouple the two crosses, a 9-3/16 in. diameter tee with an adjustable stub tuner is installed between the crosses.

The remaining 9-3/16 in. diameter port of each of the 5-way crosses is connected to an adjustable stub tuner. The stub tuner is 9-3/16 in. diameter, 50 Ohms, and is used to null the reactive impedance at the 5-way junction, arising primarily from the decoupler tee and stub. With these two stub tuners and the decoupling stub, the power flow to the crosses from the transmitter can be balanced. The impedance, as seen from the transmitter, is higher than 50 Ohms and is transformed to 50 Ohms by the combination of the transformer section, and the phase shifter/stub tuner set.

The final elements that control the loop phasing are a 3 dB hybrid for power splitting the feed from the transmitter and a 360° phase shifter which sets the overall phase difference between the two 5-way crosses [1,4]. The 3 dB hybrid is optimized to split the power from the transmitter over the 60 to 120 MHz band.

In addition to the main elements described above for phase control, other transmission line components were included for personnel safety, ease of testing, and improved reliability. Some of these components are (1) test sections which allow the high power center conductor to be quickly removed and linked to two type N connectors; (2) a four-port coaxial switch to allow the transmitter to be switched from the 3 dB hybrid to the dummy load; (3) gas barriers which allow the system to be pressurized to 3 atm (each transmission line has five separate zones) with insulating gas such as dry air,

N_2 or SF_6; (4) dc breaks which electrically isolate the transmitter and impedance matching equipment from the DIII–D torus and torus hall (the dc break's standoff is 30 kV continuous and the rf insertion loss is less that 0.05 dB); and (5) flex sections to allow for thermal growth and installation mismatch.

4. ANTENNAS

Antennas for plasma current drive optimize the unidirectional wave launch, with a wave phase velocity chosen to match the central electron velocity while simultaneously minimizing the power launched in the opposite direction [2]. The variables that affect antenna directionality are the number of radiating elements, their width and configuration, strap-to-strap spacing, the spacing from the back wall and sides, frequency, phasing, and the distance from the plasma edge

The FWCD antenna for DIII–D was designed to be modular in nature, with each antenna consisting of four modules mounted side by side in one of the larger DIII–D midplane ports. Each module of an antenna is capable of handling 1 MW for pulses up to 10 seconds which means that each antenna could support a total power of 4 MW with appropriate antenna/plasma impedance loading. Each module is fed by its own vacuum feedthrough and then external to the vacuum vessel are interconnected by coaxial transmission line eventually connecting to the high power rf transmitter [3]

Each module consists of a cavity box, Faraday shield, current strap, and vacuum coax. The cavity box, Faraday shield and current strap are tilted to match the nominal magnetic field lines at the surface of the plasma to minimize impurity production [6]. Cooling channels are fabricated into the modules to remove heat caused by rf and plasma heating. The Faraday shield rods do not have water flowing through them so that if a rod was melted by wayward plasma particles the vacuum integrity of the vessel would not be compromised by a water leak. This causes the Faraday shield rods to be only edge cooled and are thus the limiting factor for experimental pulse length.

The current straps are grounded at two locations: one end of the strap is grounded at the bottom of the cavity, while the other end is grounded to the side wall of the cavity midway up the wall, as shown in Fig. 3. The feed to the strap is attached to the back of the strap as the folded strap comes closest to the cavity wall. The folded strap design allows the antenna to have maximum performance at the high frequency end (f ≥ 80 MHz) while maintaining effectiveness at lower frequencies as well. The cavity walls are recessed to increase directionality and was achieved by wrapping the Faraday shield rods over like a croquet wicket and then connecting them to the cavity box. All parts are nickel plated to reduce sputtering and thus maximize voltage standoff capability

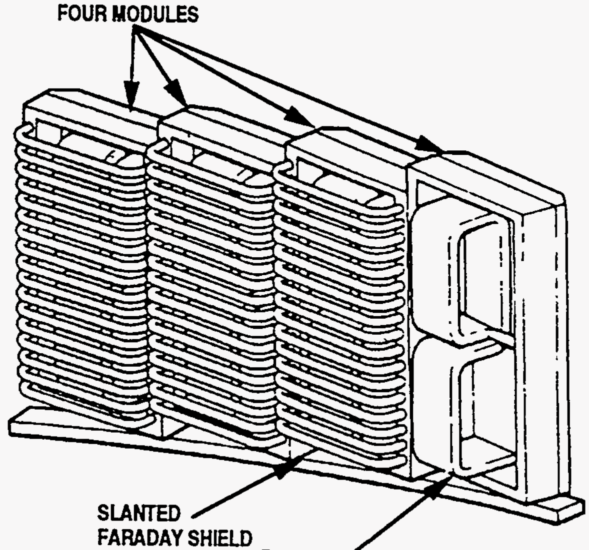

Fig. 3. Modular four-strap antenna

5. SUMMARY

This paper has presented the design of two new fast wave current drive systems for the DIII–D tokamak to support its advanced tokamak experimental program. These systems have been installed and are being commissioned.

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