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Upgrade of the DIII-D RF Systems*

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ABSTRACT

The DIII-D Advanced Tokamak Program requires the ability to modify the current density profile for extended time periods in order to achieve the improved plasma conditions now achieved with transient means. To support this requirement DIII-D 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, an all ceramic insulated transmission line, 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 with centrally localized current drive enhancement. For off-axis current modification, plans are in place to add 110 GHz electron cyclotron heating (ECH) power to DIII-D. Initially, 3 MW of power will be available with plans to increase the power to 6 MW and to 10 MW.

INTRODUCTION

Designs of fusion power plants on the basis of extrapolations of presently demonstrated plasma scaling laws lead to large devices operating at high magnetic fields and large plasma currents, which in turn lead to high capital costs. Recent experiments have identified a regime of enhanced plasma performance called Advanced Tokamak (AT) operation, which could lead to smaller and steady state tokamak fusion power plants.

The DIII-D program has as one of its primary goals to explore these AT regimes, and to demonstrate the ability to sustain these types of plasmas for several relaxation times. In order to implement steady-state AT scenarios, special "tools" are required, particularly rf systems for controlling the current density profiles.

Fast Wave Current Drive (FWCD) has been chosen as the on-axis current drive technique for DIII-D. Electron Cyclotron Current Drive (ECCD) will be used for off-axis current drive.

DIII-D RESEARCH GOALS AND PLANS

The DIII-D AT program has three essential research goals: (1) to develop physics understanding of the forming and sustaining of AT configurations; (2) to establish experimental

validation of the physics of active rf current drive and efficiency optimization with bootstrap current, and (3) to combine these to provide a demonstration of optimized, long-pulse AT operations with simultaneous improved confinement, enhanced stability, and fully noninductive current drive.

An integrated demonstration of sustained noninductive plasma operation at parameters directly applicable to the design of next generation devices is the primary target of the AT experimental program. This has been defined as operation of a 2 MA fully noninductive plasma current, in a 5% β plasma, for 10 s. Modeling indicates that about 20 MW of rf and neutral beam power will be required. The research plan for achieving the AT goals is presented in Fig. 1. The first phase of the plan explores the development of the basic aspects of AT physics using transient techniques; in the second phase, plasma profile control methods will be developed and optimized and the final phase is the demonstration of an integrated noninductive, high current, high β plasma.

RF CURRENT DRIVE FOR ADVANCED TOKAMAK SCENARIOS

Recent demonstration of several possible tokamak operation modes is key to a strong basis that an AT scenario can be demonstrated. Of the four modes identified, high internal inductance H-mode (high ℓ_i), very high H-mode (VH-mode), high beta poloidal (high $\epsilon\beta_p$), and reversed shear second-stable-core discharges, two of them (high ℓ_i , and the VH-mode with second-stable-core) strongly depend on rf heating for current drive and profile control [1].

A. VH-Mode With Second Stable Core: Negative Central Shear

The goal of this scenario is to combine the high central beta capability associated with the second stable regime near the axis of the plasma (with negative central shear) with the VH-mode confinement enhancement at the edge. Maintaining the VH-mode requires control of the plasma rotation and shear in the radial electric field. This may be accomplished by using the fast wave system in an electron heating mode, (no current drive), to enhance trapped ion orbit losses. This can be coupled to the high central beta of a second-stable-core regime by generating a hollow current profile, and with a region of negative magnetic shear near the axis. The current profile can be produced by driving off-axis

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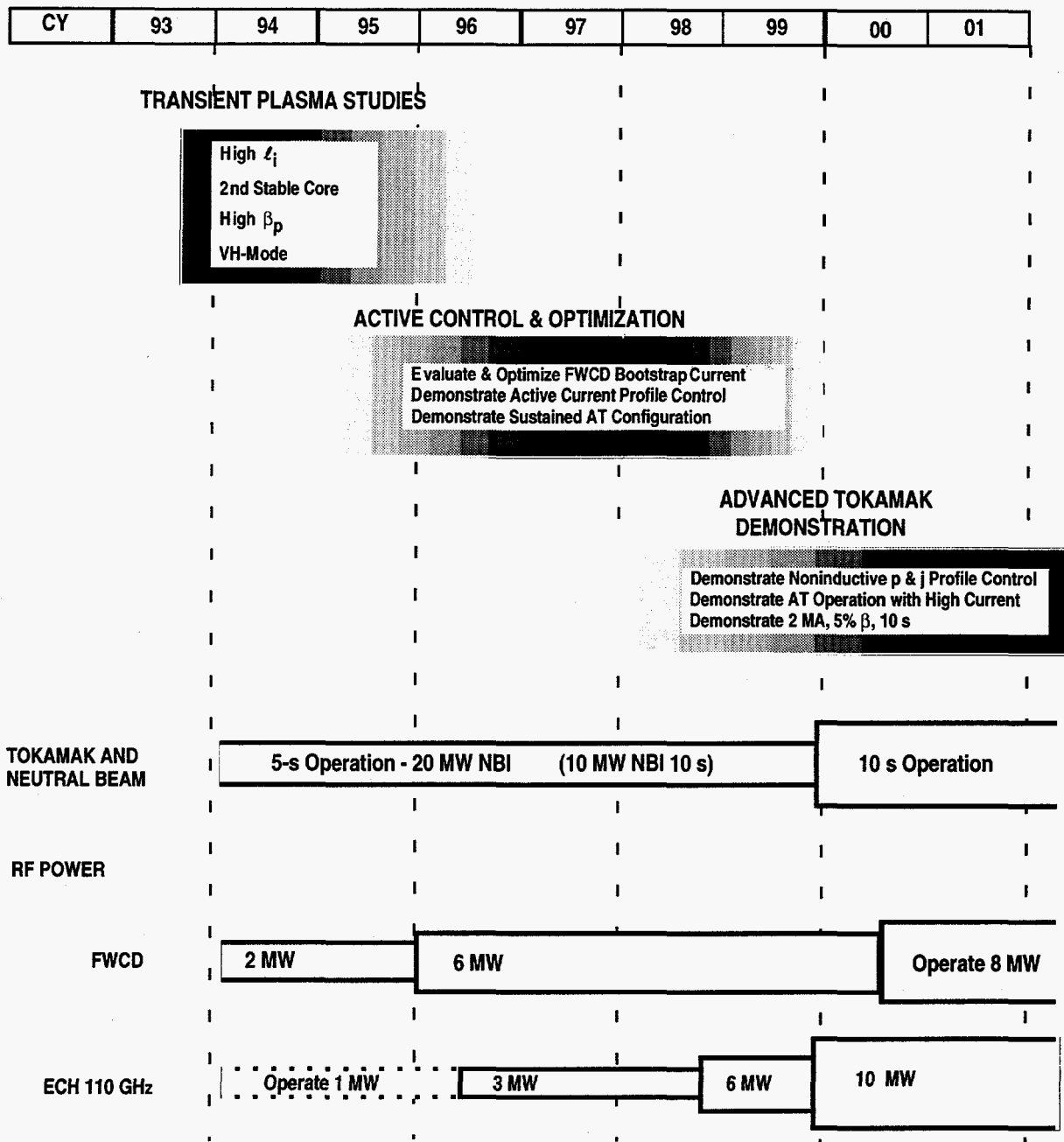


Fig. 1. DIII-D Long-Range Program Plan, program objectives and facility capabilities.

current with ECH (as shown in Fig. 2). The amount of current drive needed is dramatically reduced by the fortunate condition that the profile of the bootstrap current is close to the desired current profile. The central current density is critical for stable operation, fortunately this can be easily controlled by using some of the fast wave power in a current drive configuration. The parameters of a VH-mode with second-stable-core are given in Table I.

B. High Internal Inductance

The goal for this scenario is simultaneous operation at $\beta_N = 6$ and $H = 4$. For $I_p = 2$ MA, the bootstrap fraction is approximately 60%; however, significant central FWCD will be

needed in order to establish the peaked profile needed. The profiles for one such 1 MA discharge are shown in Fig. 3, together with the simulated parameters. This discharge can be demonstrated with the FWCD hardware now in house, while the demonstration of a full 2 MA will have to wait for the full complement of rf hardware. The parameters for the full 2 MA, high ℓ_i discharge, along with other scenarios are given in Table 1.

RF HARDWARE

The tools for creating and controlling the current and pressure profiles require a combination of rf wave heating

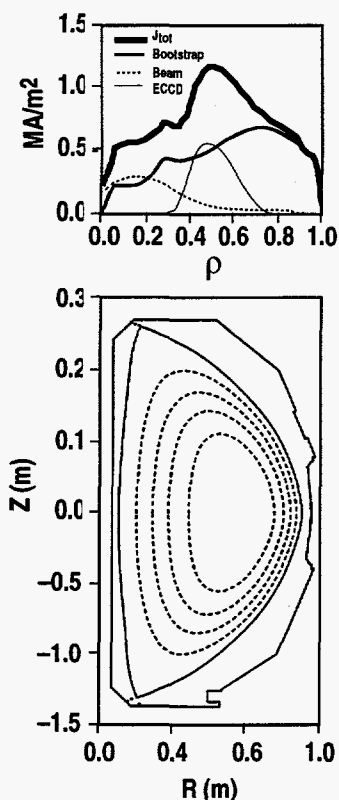


Fig. 2. VHmode with second stable-core simulated AT scenario for DIII-D. Shown are the flux surface contours and the current profile and its components ($J_{\text{bootstrap}}$, J_{beam} , and J_{ECCD}).

Table I
Advanced Tokamak Scenarios for DIII-D

Scenario	VH-Mode With Second Stable Core	High I_i	High β_p	Intermediate
β_N	5.5	6.0	6.0	4.4
H	3.5	4.0	4.0	3.0
I_p (MA)	1.6	2.0	1.2	1.6
I_i	0.6	1.3	1.3	1.0
T_e (keV)	10.6	20.0	15.9	6.3
β (%)	7.1	8.9	5.2	5.3
$I_{\text{bootstrap}}$ (MA)	1.07	1.34	1.47	1.12
I_{ECCD} (MA)	0.32	0.54	-0.37	0.18
P_{EC} (MW)	10.0	10.0	6.0	4.5
I_{FWCD} (MA)	0	0.46	0	0.07
P_{FW} (MW)	7.5	8.0	7.9	4.5
I_{NBCD} (MA)	0.17	0.18	0.21	0.10

FWCD, and FWH, as well as microwave heating ECCD and ECH. Extensive modeling of AT scenarios for DIII-D indicate that the proposed goals can be met with an 8 MW (generator power) FW system accompanied by a 10 MW ECH system (gyrotron source power) at 110 GHz [1]. The systems to meet the needs of the scenarios shown in Table I are described in the following sections. The plan for system upgrades is shown in Fig. 1.

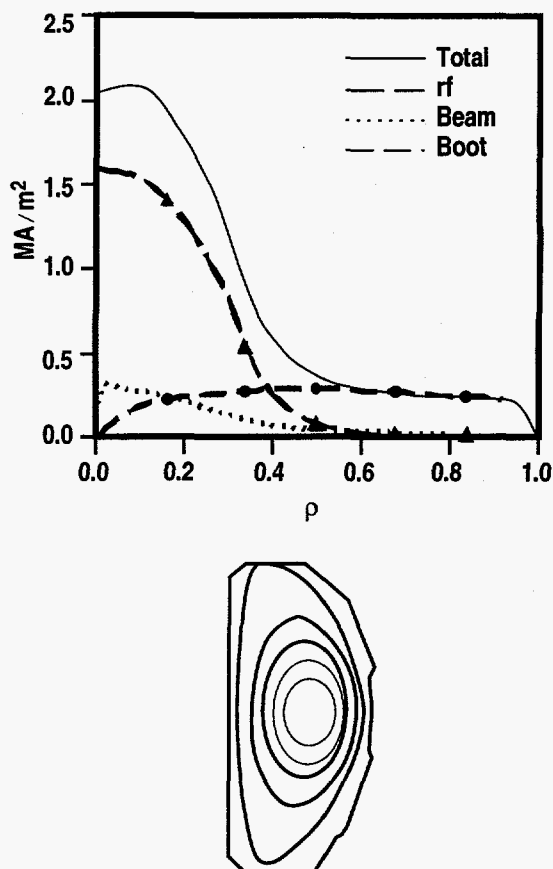


Fig. 3. High I_i simulated AT scenario on DIII-D using FWCD. Shown are the flux surface contours and the current profile and its components ($J_{\text{bootstrap}}$, J_{beam} , and J_{rf}).

A. Fast Wave Systems

The FW program on the DIII-D tokamak is a collaborative effort between General Atomics (GA) and the Oak Ridge National Laboratory (ORNL). ORNL has provided the design and fabrication of the FW antennas [2] and GA has provided the systems to generate, transmit, and couple the high power rf to the antennas.

A key element of the DIII-D FW program is the FW antennas. The DIII-D vacuum vessel has three midplane locations for antennas, as shown in Fig. 4. At 285° – 300° the original four strap antenna, FW1, [3] is located. This antenna is designed for short pulses of 2 seconds and supports operating frequencies of 30–60 MHz. At 0° and 180° are located two water-cooled four strap antennas, FW2A, and FW2B [4], which are designed to operate at a higher frequency range of 60–120 MHz, although as low as 30 MHz is possible with some efficiency degradation.

A 2 MW 30–60 MHz, FW system [3] has been in operation on DIII-D since late 1990 connected to FW1. This system has successfully demonstrated the technology of a FW system, including the transmitter, transmission and matching network, and antenna-plasma coupling in either the electron heating mode or the current drive mode.

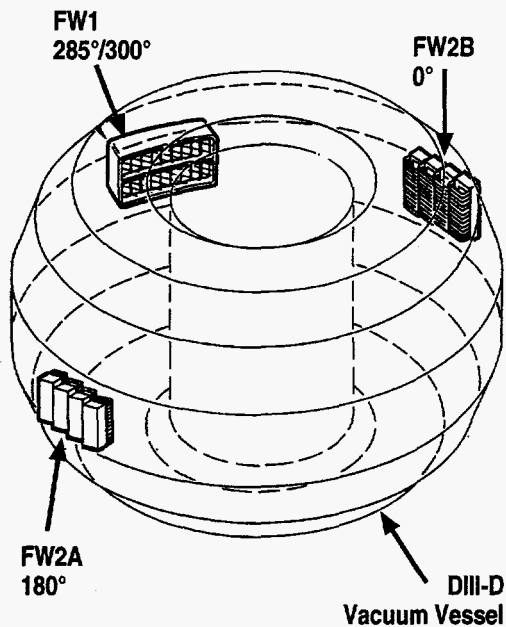


Fig. 4 Fast wave antenna locations on DIII-D.

The recently completed increment of FW power to 4 MW [5] consists of two systems each having its own 30–120 MHz transmitter with output power of 2 MW over a frequency range of 30 to 80 MHz, then decreasing linearly to 1.5 MW when the frequency reaches 120 MHz. Each transmitter is connected to a four strap antenna, FW2A or FW2B, 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 ($0, \pi, 0, \pi$) or for current drive ($0, \pi/2, \pi, 3\pi/2$), while providing matching between the antenna-plasma impedance ($\approx 1-5 \Omega$) and the

50Ω impedance that the transmitter requires for optimum power delivery. The transmission system must also compensate for the mutual inductance between the straps, which has been achieved by using a decoupler [6] developed earlier for the original 2 MW DIII-D FW system.

An overall schematic of one of the two new transmitter/antenna systems is shown in Fig 5. 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.

Since the antennas and transmission lines are rated to support 4 MW [2], the upgrade of the FW systems from 6 MW to 8 MW is a simple addition of another 2 MW, 30–120 MHz transmitter in parallel with the one connected to either FW2A or FW2B.

B. Electron Cyclotron Systems

Recently 1 MW 110 GHz gyrotrons have become available. In 1996 three ECH systems will be operational, 1 GYCOM and 2 Varian. From the experience gained testing these systems, additional power is planned to increase the power to 6 MW by the end of 1998 followed by four more systems to bring the ECH system power of 10 MW.

In order to achieve the objectives of the varied experimental uses for the ECH system, it is necessary that the microwave power be transmitted from the gyrotron to the tokamak both efficiently and with high mode purity. The latter requirement is invoked so that the radiation pattern is narrow and independent of small changes in the gyrotron operating conditions. Another requirement is that the system operate for pulses as long as 10 s.

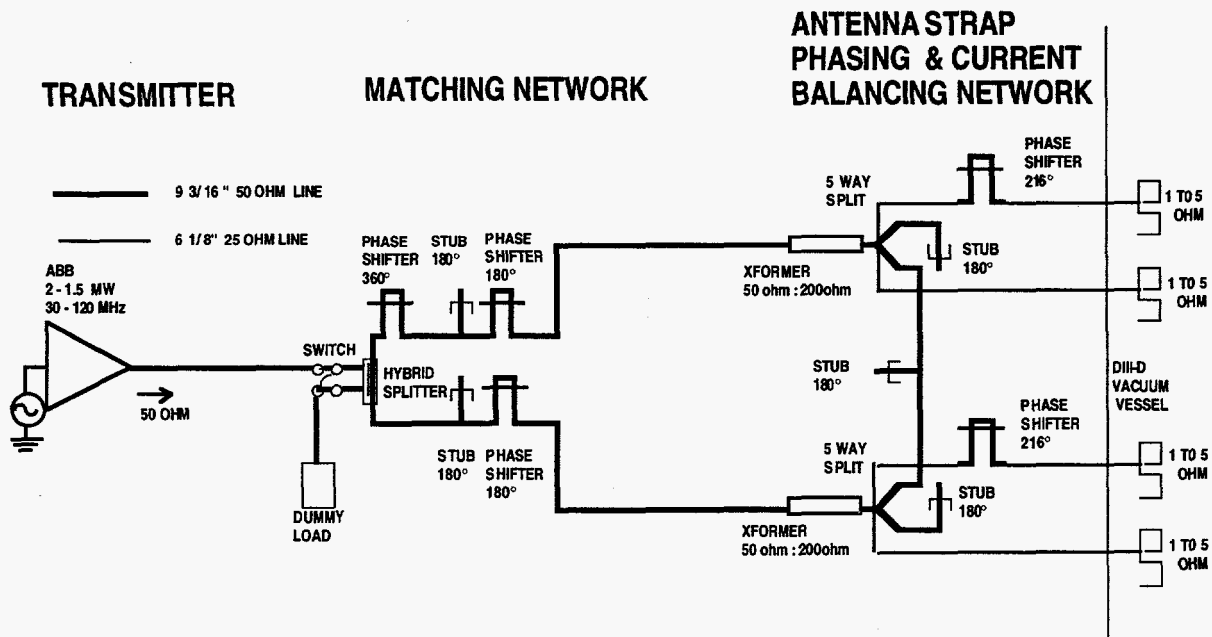


Fig. 5. Schematic for one of the 2 MW, 30–120 MHz, Fast Wave Current Drive Systems.

The method chosen to meet these objectives was to utilize the high efficiency (>30%), high power (~1 MW) internal mode-converter gyrotrons being developed in the U.S., Russia, and Japan, and to transmit the power in evacuated corrugated waveguide. A diagram of an ECH unit is shown in Fig. 6, with the main features of an ECH unit being a gyrotron tank and superconducting magnet, an internal mode-converter gyrotron, a low loss evacuated transmission line, and a quasi-optical steerable launcher. Ten such units will be needed to generate the 10 MW of ECH power required by the Advanced Tokamak experimental program.

SUMMARY

Extensive modeling of advanced tokamak scenarios have indicated that several successful profile configurations can be achieved using combinations of FWCD and ECCD. DIII-D is proceeding with a plan to upgrade the existing FW and ECH systems to 8 MW and 10 MW respectively. When these systems are fully operational, it is expected that a 2 MW fully noninductive plasma current, in a 5% β plasma, for 10 s can be demonstrated.

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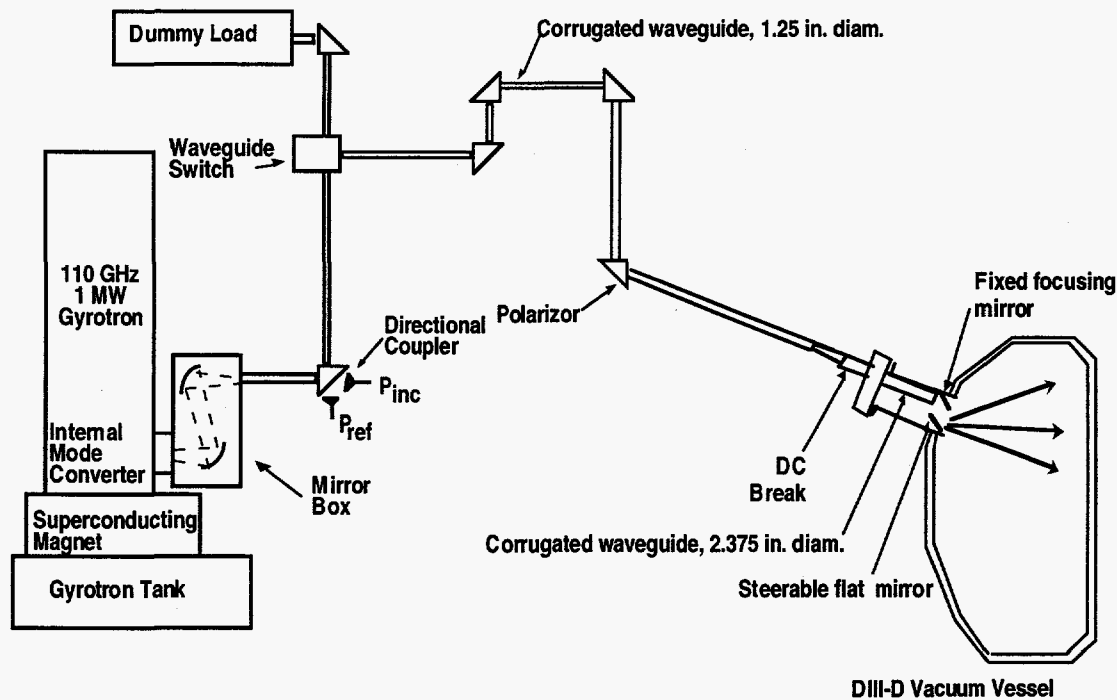


Fig. 6. 1 MW 110 GHz ECH system diagram