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DISCLAIMER

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ABSTRACT

Significant improvements are being implemented to the capability of the 110 GHz electron cyclotron system on the DIII–D tokamak. Chief among these is the addition of the fifth and sixth 1 MW class gyrotrons, increasing the power available for auxiliary heating and current drive by nearly 60%. These tubes use artificially grown diamond rf output windows to obtain high power with long pulse capability. The beams from these tubes are nearly Gaussian, facilitating coupling to the waveguide.

A new fully articulating dual launcher capable of high speed spatial scanning has been designed and tested. The launcher has two axis independent steering for each waveguide. The mirrors can be rotated at up to 100°/s.

A new feedback system linking the DIII–D Plasma Control System (PCS) with the gyrotron beam voltage waveform generators permits real-time feedback control of some plasma properties such as electron temperature. The PCS can use a variety of plasma monitors to generate its control signal, including electron cyclotron emission and Mirnov probes.

Electron cyclotron heating and electron cyclotron current drive (ECH and ECCD) were used during this year's DIII–D experimental campaign to control electron temperature, density, and q profiles, induce an ELM-free H–mode, and suppress the m=2/n=1 neoclassical tearing mode. The new capabilities have expanded the role of EC systems in tokamak plasma control.

1. EC SYSTEM

1.1. Gyrotrons and Beam Correction Optics

With the recent commissioning of two systems, ECH and ECCD are now provided at DIII–D by six 110 GHz gyrotrons (Table 1). Generated power exceeds 5 MW. Three tubes, manufactured by Communications and Power Industries (CPI) of Palo Alto, California, utilize artificially grown diamond rf output windows produced by the chemical vapor deposition (CVD) process. These tubes are rated for pulse lengths of 10 s at full power and two have been tested with 5 s pusles at 1 MW generated. The other three tubes are manufactured by Gycom of Nizhny Novgorod, Russia. These highly reliable tubes use boron nitride rf windows and are rated for > 0.75 MW at 2 s.

Table 1.
DIII–D gyrotron pulse lengths and generated powers

Gyrotron	Pulse Length (s)	Power Output (MW)
CPI-P1	0.8*	1.0
CPI-P2	5.0	1.0
CPI-P3	5.0	1.0
Gycom-1	2.1	0.7
Gycom-2	2.1	0.8
Gycom-3	2.1	0.6
	Total for > 2 s	4.1

*CPI-P1 is currently undergoing repair for a vacuum leak.

The boron nitride windows require that the rf beam exiting the gyrotron be broadened to reduce the peak intensity. Two phase correcting and focusing mirrors, housed in the matching optics unit, reconstitute the Gaussian beam for insertion into the waveguide input. The CVD diamond windows, with their lower dielectric loss and greater heat conductivity, can pass a properly formed Gaussian rf beam (Fig. 1). Only a single focusing mirror is required to insert the beam into the waveguide input. The overall power loss of the CVD diamond window and mirror system is less than half of that of the boron nitride window and mirrors, with an efficiency > 90%. The loss of the CVD diamond window by itself is less than 0.4%.

Recently the CPI-P1 gyrotron developed a minute vacuum leak through the collector water circuit while being conditioned for pulse length extension at the 1 MW level. The tube has been returned to the factory for diagnosis and repair. It is anticipated that the tube will be returned in time to participate in the 2003 experimental campaign.

1.2. Waveguide Lines and Dummy Loads

The rf beams are directed to the DIII–D vacuum vessel or to dummy loads through 31.75 mm diameter corrugated waveguides, supporting the $HE_{1,1}$ circular waveguide mode. The evacuated waveguides are up to 100 m in length (Fig. 2). With up to 14 miter bend mirrors, the transmission lines are between 70% and 85% efficient [1].

Each gyrotron system includes a 1 MW, 1 s inconel-lined tank dummy load. While power handling of these loads is adequate, heat extraction for calorimetric measurements is relatively slow and reflected power is measurable. To address these limitations, and to increase the pulse length capability, an inline preload has been installed in four systems. The water cooled preload includes an uncorrugated waveguide section causing mode conversion. This leads to attenuation in the subsequent corrugated section of the preload [2]. Heat extraction from this load is rapid, leading to quick calorimetric measurements and estimates of generated power. The combination of the two loads reduces the reflected power to very low levels, equivalent to that when the rf is routed to the DIII–D vessel.

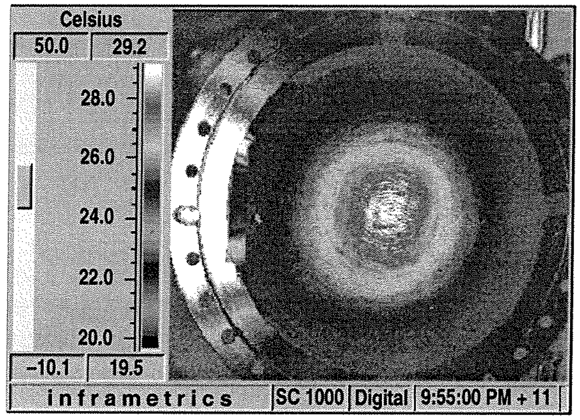

Fig. 1. A CVD diamond window can handle the peak intensity of a Gaussian 1 MW rf beam. This IR image shows the profile of the beam on a target 50 cm from the window.

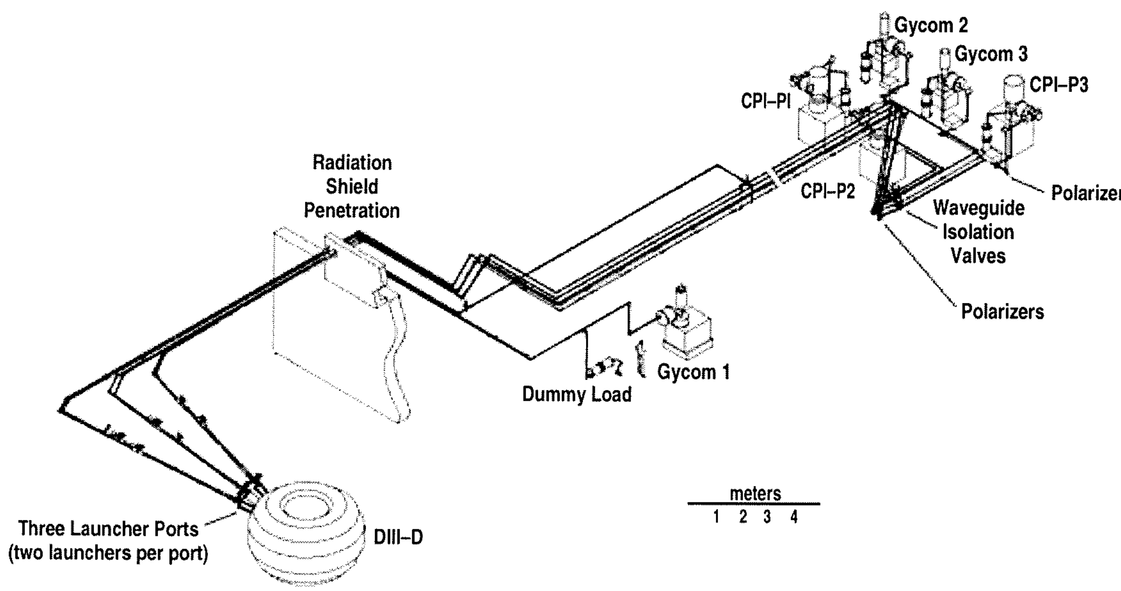

Fig. 2. The Gaussian rf beams travel from the gyrotrons to the DIII–D vessel in evacuated circular waveguides up to 100 m in length.

1.3. Polarization Control and Articulating Launchers

Control of the elliptical polarization of the rf beam entering the DIII–D vessel is provided by two rotating polarizing mirrors mounted in waveguide miter bends in each transmission line. The rotating stages, controller electronics and software for these grooved mirrors have recently been upgraded on all systems to provide reliable and smooth operation. The mirror orientations are controlled and monitored remotely from the integrated EC operator interface. The rapid movement of the rotating stages allows them to be re-homed with each change in setting. This provides confidence in the positioning of the stages. The system yields better than 95% of the power in the desired polarization.

Three dual launchers are installed on the DIII–D vessel to inject and direct the rf beams. Each provides for control of the torodial and polodial injection angles. The oldest launcher, which is now being replaced, had poloidal scan, but fixed toroidal injection angle. Its replacement and the other two lanuchers have flexible control of both the toroidal and poloidal injection angles. The two newest launchers each provide independent remote control of the torodial and polodial angles for two waveguide lines. The rapid movement capability, 100°/s, of these launchers allow for a future upgrade to real-time scanning during DIII–D experiment shots. The launchers are equipped with absolute position encoders, eliminating the need to home the launcher mirrors (Fig. 3) to establish reference positions.

The waveguide lines to these launchers can be reconfigured to allow any gyrotron to be directed to any launcher, allowing optimal use of the equipment.

1.4. Control and Instrumentation System

The integrated EC control system consists of individual gyrotron control computers networked to control, status, and data servers. The servers are also networked to operator console computers. From these consoles, or any other computer on the internal network, operators can control and monitor any combination of gyrotrons. Timing signals are provided by 80 MHz, 32 bit counter-timer modules, resulting in high time resolution. The reference waveforms for the gyrotron beam voltages are provided by Wavetek 395 100 MHz arbitrary waveform generators. Gyrotron waveforms and calorimetric temperature and flow data are collected with 12 bit digitizers.

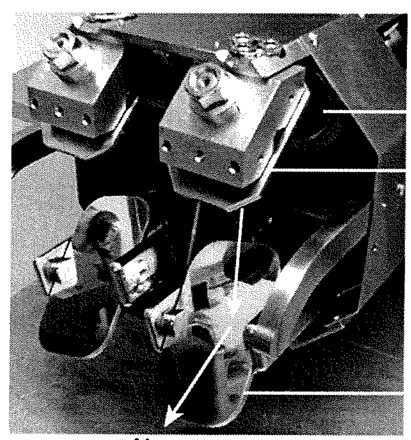

Fig. 3. A high speed dual launcher with two axis movement for each rf beam.

The Wavetek 395 allows for versatile modulation of the gyrotron voltage to control the rf output. The rf output can be swept from full to minimal power with about a 20% decrease in beam voltage. Since the beam voltage is not pulsed off, transients are minimized. The gyrotron remains in mode at low output during modulation minima. The Wavetek 395 is programmed to provide the beam voltage ramp-up and ramp-down, rectangular, triangular and sinusoidal modulation, and the pulse flat top level.

The Wavetek 395 also includes an external amplitude modulation input which is now being used to allow modulation of the beam voltage by the DIII–D PCS. The PCS can use a variety of monitors, including plasma electron temperature, to provide its gyrotron modulation signals. These signals are then conditioned to modulate the preprogrammed beam voltage reference waveform within acceptable gyrotron operating limits.

2. DIII–D ECH/ECCD EXPERIMENTS

The new ability to modulate the gyrotron rf power with a feedback signal from the DIII–D PCS was used to control the profile of the plasma electron temperature during the early phase of a DIII–D shot. ECH and ECCD were also used to help control the density and q profiles in quiescent double barrier (QDB) plasma shots. In experiments exploring the use of ECH to induce the transition from L– to H–mode in plasmas, about 2 MW of ECH resulted in a decisive ELM-free H–mode. Nearly 3 MW of injected ECCD power was used to suppress, for the first time, the m=2/n=1 neoclassical tearing mode. For this experiment, the PCS was used to move the q=2 surface past the peak of the ECCD profile to achieve suppression of the mode.

3. SUMMARY

The recent installation of additional high power gyrotrons to the DIII–D ECH system has enabled new advanced tokamak and MHD instability control experiments to be conducted. New capabilities, such as power modulation by PCS feedback signals and high speed fully articulating launchers, are also increasing the breadth of experimental possibilities. The addition of high power, long pulse length preloads to the dummy loads and ongoing improvements to the control system hardware and software have increased our ability to characterize and exploit high powered, long pulse length gyrotrons.

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