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DESIGN AND PERFORMANCE OF THE 110 GHz ELECTRON CYCLOTRON HEATING INSTALLATION ON THE DIII–D TOKAMAK

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ABSTRACT

The 110 GHz Electron Cyclotron Heating System on the DIII–D tokamak is being upgraded by the installation of additional gyrotrons, versatile launchers, and an improved control system. A total of six gyrotrons in the 1 MW class will be available for experiments during the 2001 experimental campaign. The installation will be described and the operational experience to date will be presented.

I. INTRODUCTION

The 110 GHz Electron Cyclotron Heating System (ECH) on the DIII–D tokamak is undergoing an extensive expansion. When the expansion is complete, five 1 MW class gyrotrons will have been commissioned. Three of the tubes will be able to pulse for ten seconds. The versatility of the system for tokamak experiments is also being improved by the incorporation of launchers capable of steering the rf beam inside the tokamak poloidally and torodially. One such launcher has already been installed and successfully used.

Three of the tubes are part of the Upgrade to 6 MW Program. These gyrotrons use CVD diamond windows to obtain the high power with long pulse capability. The rf beam from these tubes is nearly Gaussian, and requires less correction optics to couple to the $HE_{1,1}$ mode in the circular waveguide than the earlier gyrotrons.

During the Upgrade Program, two systems, based upon Gycom gyrotrons, were obtained from the Tokamak de Varennes program in Quebec. These were incorporated into the Upgrade Program installation. The equipment was located in future growth areas installed as part of the program, and the interface to the master ECH control system was done through equipment installed for the second and third Upgrade tubes.

The Upgrade Program presented the opportunity to redesign aspects of the existing ECH system. Pulse control and data acquisition were changed to the compact PCI format, which increased speed and versatility while reducing cost. The gyrotron tanks were redesigned to minimize the oil volume and enhance access. Conduits and waveguides were routed under a raised tile floor.

Five distinct gyrotrons were used in this year's tokamak campaign, with up to four in operation simultaneously. System architecture changes and data from the gyrotron checkout and from DIII–D experiments will be presented.

II. ECH SYSTEM CHANGES

DIII–D began operating 110 GHz, 1 MW class gyrotrons in 1996, with the commissioning of a Gycom Centaur GLGF110/1.0. Two CPI VGT-8011A tubes were added in 1997 and 1998. Successful fusion experiments with the first two tubes[1–3] led to the inception of a program to add three more tubes. During this program, two Gycom tubes were acquired from the Tokamak de Varennes program in Canada. Table I lists the 1 MW class gyrotrons at DIII–D and current status. Figure 1 identifies major components of the ECH system.

Gyrotrons. The new CPI Production tubes are all of the diode gun design, which it is anticipated will be more

TABLE I. CURRENT ECH GYROTRON STATUS

Gyrotron	Operational	Gun/Window	Nom. Power	Nom. Pulse	Status
Gycom* 1	1996	Diode BN	0.7 MW	2 s	Ready for operations, waiting for new high voltage power supply
CPI# Development 1	1997	Triode Sapphire	0.7 MW	1 s	Damaged filament repaired, needs reconditioning
CPI Development 2	1998	Triode CVD Diamond	0.7 MW	2.5 s	RF output window cracked, fate not decided
CPI Production 1	2000	Diode CVD Diamond	1.0 MW	10 s	RF output window leak repaired, will be reconditioned soon
CPI Production 2	2000	Diode CVD Diamond	1.0 MW	10 s	Ready for limited operations, acceptance testing in progress
CPI Production 3	est. 2001	Diode CVD Diamond	1.0 MW	10 s	Undergoing factory conditioning
Gycom 2	2000	Diode/BN	0.7 MW	2 s	Ready for operations
Gycom 3	2000	Diode/BN	0.7 MW	2 s	Ready for operations

*Gycom, 46 Ulyanov St., Nizhny Novgorod, Russia.
#CPI, Communications and Power Industries, 355-T Hansen Way, Palo Alto, California, USA.

reliable as a system than the triode guns on the CPI Development tubes. The additional high voltage regulator required by the triode gun are not necessary for diode tubes. Each of the TdeV Gycom tubes, which are being used in as close to the in-house TdeV configuration as reasonable to facilitate reinstallation, has its own modulator-regulator (mod-reg) high voltage system. These are fed by a single requlated high voltage power supply, capable of 80 A at 80 KV. Although the use of two series requlators to operate each gyrotron intoduces complexity, this allows the two gyrotrons to be controlled by different cathode voltage reference waveforms. It also allows the possibility that the mod-regs can be powered by an unregulated dc source in the future, freeing up the present regulated source.

The CPI Production tubes and CPI Development 2 use chemical vapor deposition (CVD) grown diamond windows. The rf loss in these windows is very low, less than 0.4%, which should eliminate the window as a limit on 1 MW continuous operation, with proper window edge cooling. CPI Production 2 and 3 utilize a high temperature

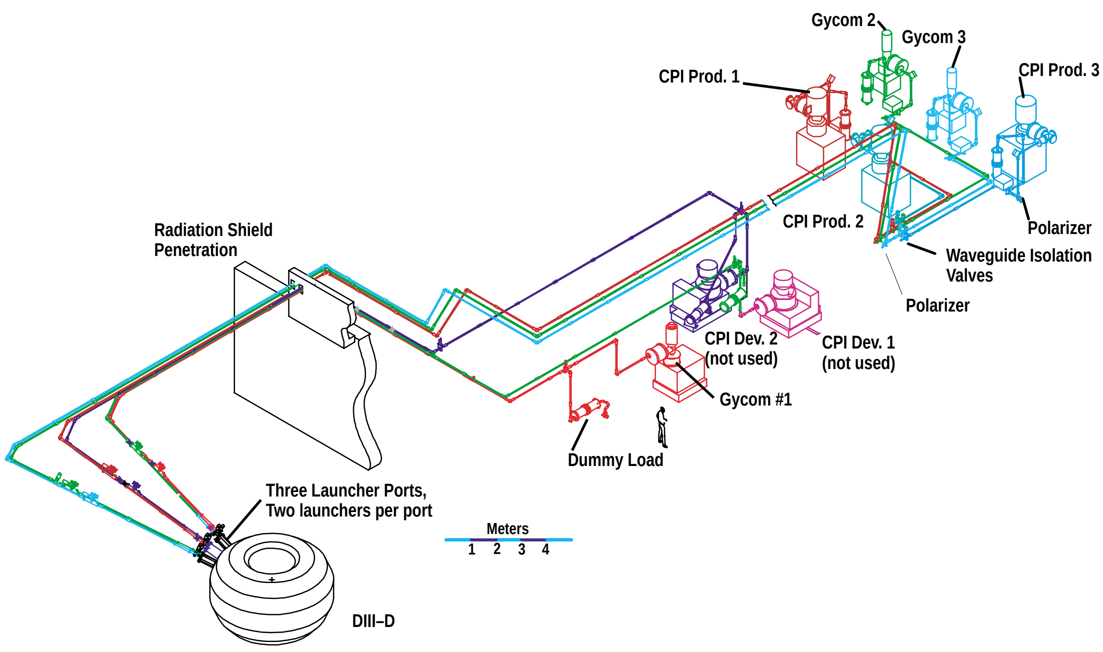

Fig. 1. DIII–D ECH system.

braze newly developed by CPI. This eliminates the previous use of aluminum seals in the water channels. The aluminum seals on CPI Development 2 and CPI Production 1 failed due to corrosion, despite the use of an anticorrosion agent.

Tanks. The oil tanks containing the high voltage connections to the CPI Production gyrotrons were redesigned from the tanks used on the Development tubes. The new tanks use a greatly reduced oil volume. This helps when the oil has to be drained to gain access to the high voltage connections. It also reduces the size of oil spill containment structures. Another change, made possible by the use of diode guns, was to move all monitoring electronics to outside the tank, out of the oil. Only the high voltage snubber remains inside the tank.

Waveguide Lines. The use of the CVD diamond windows allows the rf beam exiting the gyrotron to be nearly a true Gaussian. Previously, the beam power profile was flattened and spread to avoid hot spots on lossier windows. With a true Gaussian exiting the gyrotron, phase correction mirrors are no longer needed. A focusing mirror is still used, though, to direct the beam into the 31.75 mm waveguide.

A new steerable launcher, designed by the Princeton Plasma Physics Laboratory (PPPL), was installed on one of the ECH ports in the DIII–D vessel. Previous launchers, which direct the rf beam from two gyrotrons into the plasma, had a fixed toroidal angle and an externally steerable polodial angle. The PPPL launcher adds steering to the torodial angle which is independent for each gyrotron. Additionally, the launcher is fully remotely actuated. Control is through a programmable logic controller (PLC). The rf beam can be steered through a 35° range toroidally, nearly centered on the perpendicular, and 30° polodially, giving access to the tokamak upper half plane.

Reliability was improved by upgrading the actuator used on the waveguide polarizer mirrors. These mirrors, which have a grooved reflection surface, allow full control of the elliptical polarization of the rf beam. The new actuators have an auto-homing function which makes the relative encoder practical for determining mirror orientation. The actuators also have a knob that can be used to change the polarization if the electronics fails.

Remotely actuated waveguide gate valves, used to isolate the waveguide in the gyrotron hall from the waveguide line going to the DIII–D vessel, were introduced on CPI Development 2. Operation of the valve is controlled by logic in the ECH PLC. They continue to be used on the new tubes, increasing operator productivity during DIII–D experiments.

Control System. All new construction allowed the control system to be repackaged. Each new gyrotron system now has its own set of racks, and each set is initially identical, increasing construction productivity. The systems make extensive use of patch panels, which has greatly enhanced their flexibility.

Each new gyrotron has its own computer, networked to the master control server, to run gyrotron control processes. This computer, and the pulse generation and data acquisition electronics, were changed to the compact PCI (cPCI) format. The computers formally used were desktop format, the pulse generator was a standalone chassis, and the data acquisition was CAMAC based. The move to cPCI greatly reduced the size of the hardware. The pulse generation and data acquisition modules are faster but less expensive than the previous equipment. Pulse generation is now based upon an 80 MHz clock. Waveform data can be acquired at channel rates up to 70 KHz. Fault data has a 10 MHz channel sampling rate.

The master control server was previously hosted on a Sun SparcStation 20. It is now hosted on a Pentium III workstation running Windows NT. There was an increase in speed over the older equipment as anticipated. The use of a Windows family operating system on all ECH computers makes it easier to set up and maintain the systems.

Power Supply. The standard ECH high voltage power supplies were extensively modernized to support the Upgrade Program. The supplies are designed to handle the nominally 80 KV, 80 A load of two gyrotrons, and can be modulated 15% in voltage at 20 KHz.[4]

Building Addition. A building addition was required to house the new gyrotrons and their support hardware. Two of the new rooms, the gyrotron hall and the gyrotron electronics room, were built with a raised floor with removable tiles. Waveguide, cables, and water mains are under the floor, nearly eliminating floor and overhead clutter. The gyrotron hall was designed with a wide center corridor, making it easy to bring in and out diagnostic equipment.

The new addition also features a two ton overhead crane. The crane services the entire ECH portion of the addition, including the gyrotron hall, electronics room, and high voltage power supply expansion bay.

III. GYROTRON CONDITIONING

During factory checkout, CPI Production 1 produced 1.04 MW for pulses of less than 10 ms with a beam current and voltage of 40 A at 80 KV. In long pulse mode, it produced 546 KW for 10 s with a beam current and voltage of 25 A at 80 KV. High power/long pulse width tests were not possible at the factory due to limitations of their power supply. The highest power achieved at DIII–D was about 500 KW for 100 ms. This gyrotron suffered an output window seal failure and so could not be conditioned further.

During its factory checkout, CPI Production 2 produced 1.05 MW for pulses of less than 10 ms with a beam current and voltage of 39.4 A at 80 KV. It also produced 510 KW for 10 s with a beam current and voltage of 26 A at 78 KV. During conditioning at DIII–D, the highest average power into a load was 750 KW for 220 ms. This was with a beam current and voltage of 38 A at 78 KV. The longest rf pulse was 5 s at 476 KW with a beam current and voltage of 31 A at 78 KV.

IV. EXPERIMENTAL RESULTS

Several important scientific results were achieved with ECH systems during the 2000 campaign. Perhaps the most significant was the complete suppression of a neoclassical tearing mode with EC current drive (ECCD). Additionally, electron transport barriers were formed and studied, electron temperature was raised to 15 keV, four 1 MW gyrotrons were fired during the same tokamak shot, the PPPL launcher was used for co- versus counter-drive experiments on the same day, and polarizer settings and their predicted effect were experimentally verified.

The suppression of the neoclassical tearing mode can occur if the deficit/bootstrap current in a rotating island with reduced pressure gradient can be placed. This can be accomplished by co-ECCD driven at the location of the island. Suppression required identifying this location.

A sweep of the magnetic field, which determines where the rf power will be absorbed, was done to find an optimal value. A shot with this optimal value (DIII–D shot 104328) resulted in the complete suppression of the tearing mode. The suppression was accompanied by a rise in beta (plasma energy/magnetic energy) and a rise in neutron emission. These effects, including the suppression, continued for a while after the current drive pulse ended (See Fig. 2).[5]

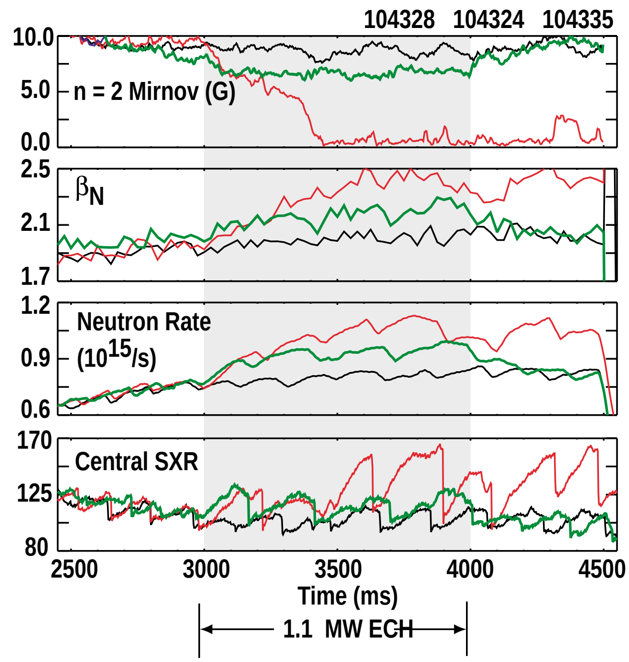

Fig. 2. Neoclassical tearing mode suppression. Traces from three discharges, one with ECCD applied at the q=3/2 surface (thin grey) near ρ=0.6 and one with the ECCD moved 2 cm away from that surface (thick light grey), and one with no ECH (black)but otherwise identical. (a) amplitude of the n=2 Mirnov signal, (b) normalized beta, (c) neutron rate, and (d) central X–ray emissivity showing sawteeth. 1.1 MW of co-ECCD is applied during the shaded time.

This experiment demonstrated the highly localized nature of the ECCD. Sweeping the magnetic field, and hence changing the deposition location of the ECCD, showed that the ECCD is most effective when deposited at the center of the magnetic island forming the tearing mode. This is consistent with theory. The sensitivity of the amplitude of the tearing mode to deposition location suggests that the width of the ECCD profile is smaller than the island width of about five centimeters. This is consistent with ray tracing calculations. The calculated amplitude of the driven current density exceeded that of the local bootstrap current density. This is also a requirement for stabilization.[6]

V. SUMMARY

The ECH Upgrade to 6 MW Program is nearly complete. Four 100 GHz, 1 MW class gyrotrons were recently commissioned and used for DIII–D experiments in addition to an existing tube. Up to four tubes were used in experiments at one time. Several important experimental results were obtained, including the complete suppression of a neoclassical tearing mode.

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