STATUS OF THE ELECTRON CYCLOTRON HEATING SYSTEM ON DIII–D

*I.A. Gorelov, J. Lohr, D. Ponce, R.W. Callis, and K. Kajiwara**

General Atomics, P.O. Box 85608, San Diego, California 92186-5608 USA
**ORISE, Oak Ridge, Tennessee, USA*

e-mail: gorelov@fusion.gat.com

A high power, long pulse 110 GHz electron cyclotron system is in operation on the DIII-D tokamak. Up to six gyrotrons have been operated simultaneously for plasma physics experiments. Following a vacuum failure on one of these tubes, five gyrotrons are still in productive service. The DIII-D program will test a new single stage depressed collector gyrotron, which has been designed to generate 1.5 MW. It is possible that quasi-continuous operation at full power will be achieved with this development unit. The rf generated by these gyrotrons is transmitted to the tokamak by a 90 m long evacuated corrugated wave guide which incorporates polarization control, path switching, isolation, beam pointing and rf power measurement functions. The components of these lines were designed to operate at 1.0 MW for up to 10 s pulse length. Increasing the generated power will require modifications to some of the components. The long term upgrade plans for the DIII-D ECH installation will be presented.

1. Introduction

The 110 GHz gyrotron complex has been installed at the DIII-D facility to provide the rf power required for various electron cyclotron heating (ECH) and electron cyclotron current drive (ECCD) experiments. The installation presently consists of five 1 MW level gyrotrons, plus the necessary transmission components, dummy loads, polarizers, waveguide switches and launchers. The generated rf power is delivered to the tokamak by six evacuated windowless low loss transmission lines. Three fully articulating dual launchers, two of which are capable of high speed spatial scanning, can steer the rf beams poloidally and toroidally. Total injected rf power exceeded 3.5 MW during the 2003 experimental campaign.

Infrared measurements of the temperatures of gyrotron output diamond windows indicated that some windows became contaminated either during brazing and/or bakeout. As a result, diagnostic procedures were initiated to evaluate the conditions of production windows being placed in service. Results of infrared diagnostic measurements of window temperatures and contamination will be reported.

A feedback system linking the DIII-D Plasma Control System (PCS) with the gyrotron beam voltage waveform generators permits real-time feedback control of plasma properties through control of injected power. Slow power ramps and control of the electron temperature at specific locations in the plasma have been tested under PCS control in addition to pre-programmed modulation with a variety of waveforms at frequencies up to 10 kHz.

2. Gyrotrons

A total of six gyrotrons in the 1 MW class were available simultaneously for experiments during the 2003 experimental campaign (Fig. 1), including three Communications & Power Industries (CPI) gyrotrons with chemical-vapor-deposition (CVD) diamond windows and three GYCOM gyrotrons with boron nitride output windows.

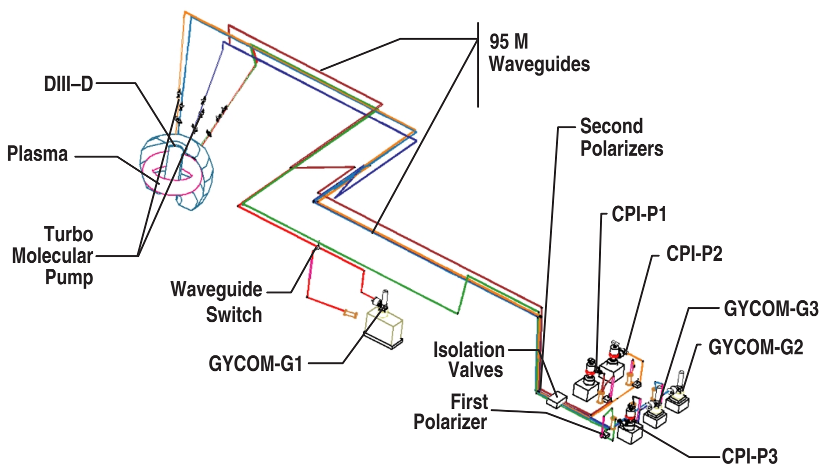

Fig. 1. Layout of DIII-D ECH system in 2003.

Window heating limits the long pulse capability of the GYCOM gyrotrons. Typical rf absorption in these windows is 4%, so the central temperature of the boron nitride windows can increase to ~950°C during a two second pulse with output rf power near 860 kW. To reduce the peak power loading on the windows, the rf beam exiting the gyrotron is intentionally broadened to a non-Gaussian profile [1]. This broadened beam cannot efficiently be coupled directly to the waveguide, therefore two phase correcting and focusing mirrors, housed in the matching optics unit (MOU) following the gyrotron window reconstitute the Gaussian rf beam for insertion into the 31.75 mm corrugated waveguide. This process has relatively poor efficiency. As a result, 15%–17% of the rf power transmitted through the window is lost in the MOU. The CVD diamond windows on the CPI gyrotrons absorb only ~0.2% of the transmitted rf power and can pass a properly formed Gaussian rf beam without damage, so only a single focusing mirror in the MOU is required to couple the rf beam into the waveguide. The coupling losses for these gyrotrons do not exceed 5%–7% of the total transmitted power.

The temperatures of the diamond windows are measured during gyrotron pulses using infrared imaging (Fig. 2) with an appropriate measured emissivity. The maximum central window temperature stabilized after ~2 s pulse duration and did not exceed 130°C during a 5 s pulse with output power >900 kW.

Two anomalies were observed. Isolated hot spots were seen on all the diamond windows and unexpectedly high central temperatures also were measured on some, but not all, of the windows (Fig. 3) [2]. The anomalies were nvestigated using Raman scattering and direct thermocouple measurements of the window temperatures. These showed that the windows, which appeared in the infrared to be hottest, had thin layers of graphite on the window surfaces but no bulk contamination. The coatings slightly increased the rf absorption resulting in higher temperatures, but a larger effect was the increase in emissivity, which biased the infrared measurements to higher temperatures. It was subsequently found that a graphite film could be deposited on the diamond surfaces during the AuCu braze procedure. Although the coatings could be removed on the outer surfaces of the windows, the inner surfaces could not be cleaned. Once the problem was understood, appropriate measures were taken during manufacture of the gyrotrons to avoid contamination.

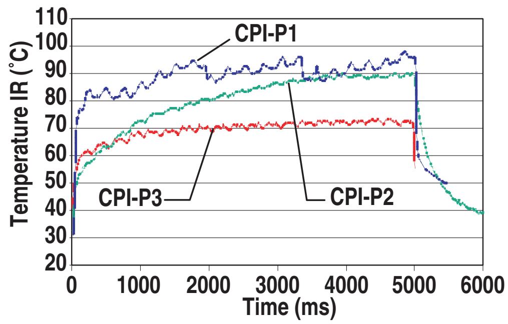

Fig. 2. Evaluation of diamond window temperature during 5 s pulse, output power more than 900 k

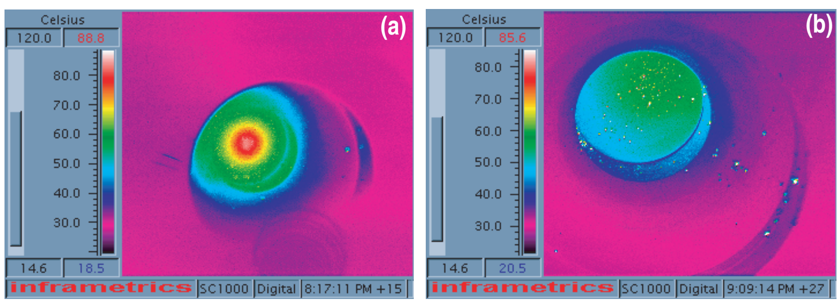

Fig. 3. (a) IR image of diamond window of CPI-P2 contaminated with a thin layer of graphite on the surface; (b) IR image of the diamond window of CPI-P3.

Of the eight 110 GHz 1 MW level gyrotrons which have been installed and tested on DIII-D, three have generated spurious parasitic emission near 100 MHz. Both triode and diode guns have exhibited this emission. The frequency is consistent with the transit time for electrons reflected from the magnetic mirror field at the cavity and trapped between the cavity and the gun. The power has been measured to be several kW. In Fig. 4, the parasitic emission spectra from the three gyrotrons are shown. It should be noted that this emission arises after a cer-

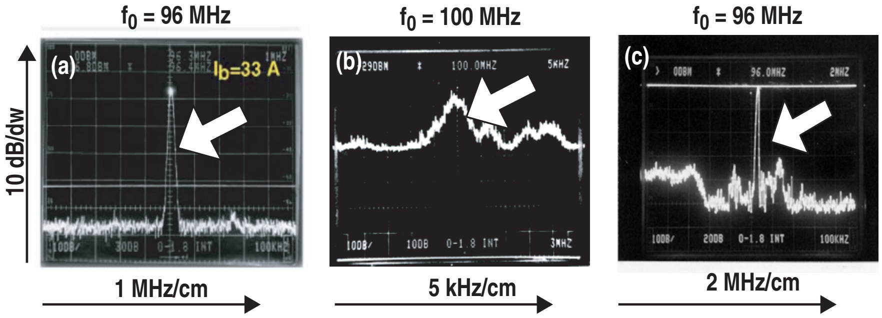

Fig. 4. (a) Parasitic emission spectra for GYCOM-G1 near 100 MHZ, (b) parasitic emission spectra for CPI PROTOTYPE-2, (c) parasitic emission spectra for CPI-P2.

tain time of operation during a gyrotron pulse. Presumably, some changes in the cathode occur which have the effect of increasing alpha, the electron pitch angle for some electron, resulting in an increase in the fraction of reflected electrons.

3. Transmission lines and articulating launchers

The transmission line system connects the gyrotrons to the launchers on the DIII-D tokamak using evacuated corrugated waveguide with a 31.75 mm inside diameter. Typical waveguide pressures of 10^{-6} torr can be maintained by turbo-molecular pumps at each end of the transmission lines. Each line comprises an MOU, miter bends, dummy loads, polarizers, waveguide switches and up to 95 m of waveguide (Fig. 5). In order to tune the gyrotron before injecting power into the tokamak, the rf power can be directed into a series combination of two dummy loads. The path to DIII-D or the dummy loads is selected by a waveguide switch in each line, which inserts a 45 deg. mirror in the transmission line.

Using a smooth wall waveguide section followed by corrugations with tapered depth, the evacuated compact waveguide load converts the low loss $HE_{1,1}$rf beam to lossy surface TM modes with wall currents that dissipate their energy on a water cooled waveguide section [4]. A waveguide bellows is incorporated to accommodate the 2–5 mm thermal expansion of the absorbing section. These loads absorb ~70% of the incident rf and a backstop Inconel load absorbs the remainder.

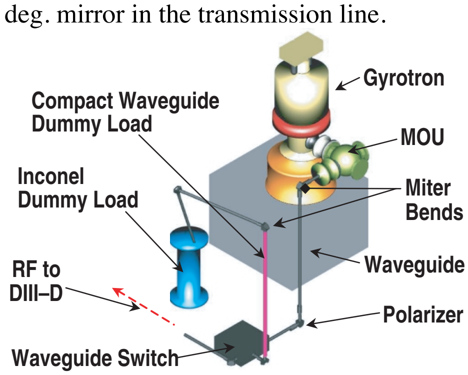

Fig. 5. Layout of transmission line system of single gyrotron.

The waveguide transmission lines in the DIII-D system include up to 14 miter bends. Each standard miter bend contributes near 1.0% loss and each of the two polarizing miters contributes 1.5% to the line losses. The total efficiencies of the transmission lines are between 70% and 80%.

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 first polarization miter, typically located in the second miter bend, has groove depth of ~$\lambda/2$ and is used to rotate the plane of the linearly polarized wave. The second polarizer with ~$\lambda/4$ groove depth separates the two orthogonal components of the electric field and gives elliptical polarization. Using both polarizers permits the excitation of pure extraordinary or ordinary mode at the plasma for arbitrary injection geometry at the second electron cyclotron harmonic for ECH and ECCD. Measurements of the linear polarization made at the last miter bend before the launcher showed better than 95% of the power was injected into the plasma in the desired polarization for several combinations of polarizer angles.

Three fully articulating dual launchers [5], are installed on DIII-D which can steer the rf beams poloidally and toroidally through ±20 deg. in each direction, as shown in Fig. 6. Each launcher has a fixed focusing mirror and a flat steering mirror. Two launchers are capable of high speed, 100 deg/s, spatial scanning to allow for a future upgrade to real-time scanning during plasma shots. Langmuir probes installed on each launcher in vacuum are used to detect arcing during rf pulses. View ports on two of the launchers accommodate video monitoring of the launchers during operation. These new diagnostics were added to forestall damage to the launchers in the event of breakdown.

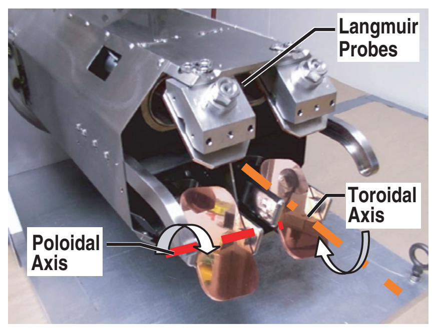

Fig. 6. PPPL fully articulating dual launchers can steer the rf beams poloidally and toroidally through ±20 deg. in each direction.

4. Plasma control system

The DIII-D PCS not only controls the plasma equilibrium and evolution during tokamak shots, but also can serve as a feedback system linking of variety of plasma parameters with the gyrotron output power. The rf output power from each gyrotron can be changed from full power to minimal power with about a 20% decrease of beam voltage. Varying the gyrotron high voltage under control of the PCS permits real-time feedback control of some plasma properties, such as electron temperature, by changing the injected ECH power [6]. The control system typically compares the time dependent ECE signal from a particular point in the plasma to a target waveform and derives an error signal which is used to control modulation of the high voltage supply of the gyrotron. An example of open loop control of the total ECH injected power is shown in Fig. 7. Each gyrotron of the four in operation was ramped up in power in sequence from zero to the maximum and then held at that output, with successive gyrotrons stacked so that the total power delivered to the plasma ramped up smoothly from zero to the maximum available, about 2.1 MW.

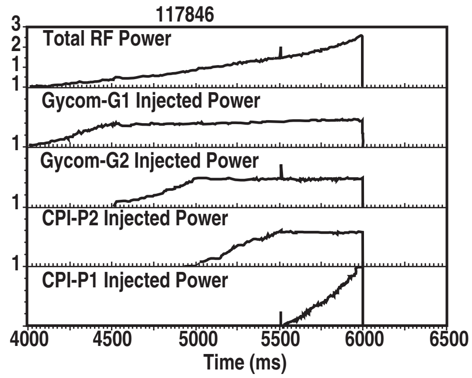

Fig. 7. Feedback control of the output power of the gyrotrons permits slowly arise injected rf from minimum level less than 100 kW up to 2.0 MW during 2 s.

5. Future plans

The DIII-D gyrotron complex is being upgraded by the addition of three more 110 GHz tubes producing 1.0 MW for 5.0 s. A fourth tube with depressed collector potential will also become part of the DIII-D system while under evaluation. This tube is a product of the U.S. gyrotron development program and is designed to produce 1.5 MW for quasi-continuous operation.

Acknowledgment

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