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Multi-megawatt 110 GHz ECH System for the DIII-D Tokamak*

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Abstract — Two 110 GHz gyrotrons with nominal output power of 1 MW each have been installed on the DIII-D tokamak. The first 110 GHz gyrotron built by Gycom has a nominal rating of 1 MW and a 2 s pulse length, with the pulse length being determined by the maximum temperature allowed on the edge cooled Boron Nitride window. This gyrotron was first operated into the DIII-D tokamak in late 1996. The second gyrotron was built by Communications and Power Industries (CPI) was commissioned during the spring of 1997. The CPI gyrotron uses a double disc FC-75 cooled sapphire window which has a pulse length rating of 0.8 s at 1 MW, 2 s at 0.5 MW and 10 s at 0.2 MW. Both gyrotrons are connected to the tokamak by a low-loss-windowless evacuated transmission line using circular corrugated waveguide for propagation in the HE₁₁ mode. Using short pulse lengths to avoid breakdown inside the air filled waveguide, the microwave beam has been measured inside the DIII-D vacuum vessel using a paper target and an IR camera. The resultant microwave beam was found to be well focused with a spot size of approximately 8 cm. The beam can be steered poloidally from the center to the outer edge of the plasma. The initial operation of the Gycom gyrotron with about 0.5 MW delivered to a low density plasma for 0.5 s showed good central electron heating, with peak temperature in excess of 10 keV. A third gyrotron, being built by CPI, will be installed later this year. Progress with the first CPI tube will also be discussed and future plans for the ECH installation and physics experiments will be presented.

INTRODUCTION

To support the Advanced Tokamak (AT) operating regimes in the DIII-D tokamak, methods need to be developed to control the current and pressure profiles across the plasma discharge. In particular, AT plasmas require substantial off-axis current in contrast to normal tokamak discharges where the current peaks on-axis. An effort is under way to use Electron Cyclotron Current Drive (ECCD) as a method of sustaining the off-axis current in AT plasmas. The first step in this campaign is the installation of three megawatts of electron cyclotron heating power. This involves the installation of three rf systems operating at 110 GHz, the second harmonic resonance frequency on DIII-D, with each system generating nominally 1 MW. The three systems will use one GYCOM [1] (Russian) gyrotron and two CPI [2]

(formerly Varian) gyrotrons, all with windowless evacuated corrugated low loss transmission lines. The GYCOM gyrotron system has been tested at the factory and installed at DIII-D [3], and to-date over 500 kW of rf power has been injected into DIII-D plasmas on a routine basis for 2 s. This paper describes the rf systems and reports on the results of the tests using the GYCOM gyrotron.

RF SYSTEM OVERVIEW

Two gyrotrons have been installed and operated on the DIII-D tokamak. One, a GYCOM gyrotron [1] has been in operation for over a year, and the second a Communications and Power Industries (CPI) gyrotron [2] model VGT-8011A has been in service since May 1997. Both gyrotrons are nominally 1 MW at a central frequency of 110 GHz. Although each gyrotron is designed for long pulse capability (>10 s), their present pulse capability is limited to 2 s and 0.8 s respectively, owing to the output windows currently installed upon the tubes. The GYCOM gyrotron uses a BN edge cooled window, and CPI uses a double disk sapphire window design with an inert Chloro-fluorocarbon (FC-75) coolant flowing between the two disks. The gyrotron performance parameters are shown in Table I. Photos of the two gyrotrons are shown in Fig. 1.

The transmission line is 31.75 mm diameter aluminum corrugated waveguide carrying the HE₁₁ mode. The waveguide diameter represents a compromise between power handling capability and the desirability that the

Table I
GYROTRON PERFORMANCE PARAMETERS

	GYGOM	CPI
Frequency, GHz	109.8 – 110.15	110
RF Output Power, kW	926.0	105–905.0
RF Pulse Duration, (kW)/s	(960)/2.0	(105)/cw, (350)/10, (400)/6, (530)/2,
Efficiency, %	38.0	32.0
Beam Voltage, kV	72.0	80.0
Peak Cavity Ohmic Loss, kW/cm ²	≤ 2.0	≤ 2.0
Beam Current, A	33.8	35

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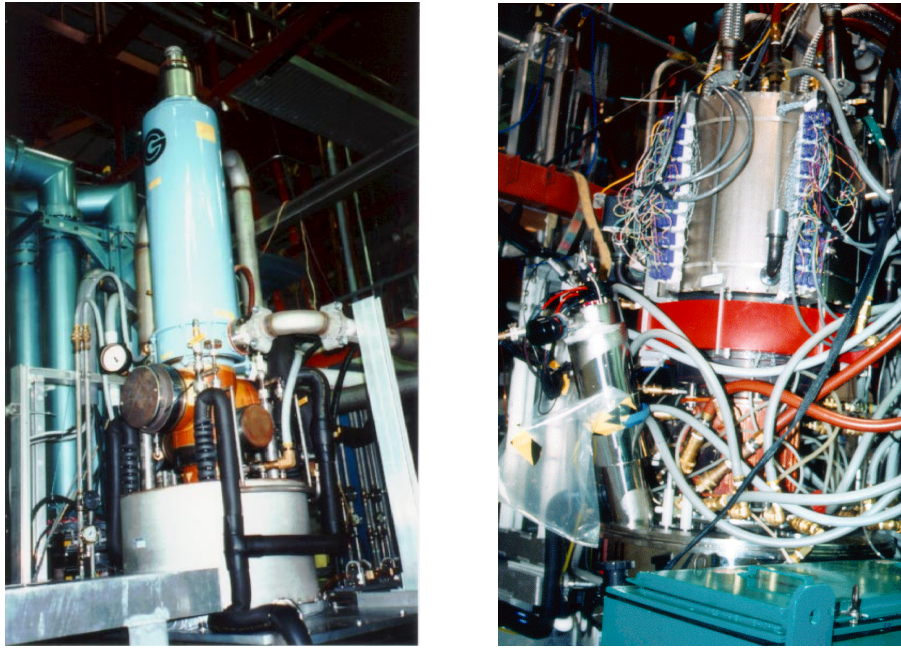


Fig. 1. Photos of the GYCOM (a) and CPI (b) 110 GHz, 1 MW gyrotrons as installed at the DIII-D facility.

transmission line be insensitive to misalignment, thermal growth, and motion. The rf beam exiting the side of the gyrotron is a modified gaussian beam with a flattened profile to minimize the peak temperature of the window, so as to produce the minimum thermal stress within the window. The window and rf beam are made as large as practical, ≈ 100 mm, to reduce the thermal load on the window. Therefore direct coupling from the gyrotron into the waveguide is impractical and an interface device is required. Using two mirrors, the rf beam exiting the gyrotron is phase corrected to restore it to a free-space Gaussian and is also focused to properly couple to the 31.75 mm waveguide diameter. The mirrors are housed in a Mirror Optics Unit (MOU) which also contains a watercooled resistive load, and absorbs any stray rf power that exits the gyrotron at an angle that can not be focused into the waveguide.

The entire transmission line system, shown in Fig. 2, consists of six mitre bends and is ≈ 40 m long with estimated 2% loss in the waveguide and 0.6% loss per mitre bend. The mitre bend losses are from mode conversion 0.5% and ohmic losses 0.1%. The waveguide is evacuated to a pressure of $\approx 1 \times 10^{-5}$ Torr by a turbomolecular pump at the MOU and a similar pump on a special section of waveguide near the tokamak, where the waveguide has been slotted to allow pumping between the corrugations. This waveguide pumping section is placed as close to the DIII-D vacuum vessel as practical so that any impurities evolving from the waveguide upstream of the tokamak can be pumped out before they reach the plasma and possibly contaminate it. However, in the case of a catastrophic vacuum failure, there is a fast shutter located just upstream of the pumping section. This shutter can close faster than the pressure wave can travel down the

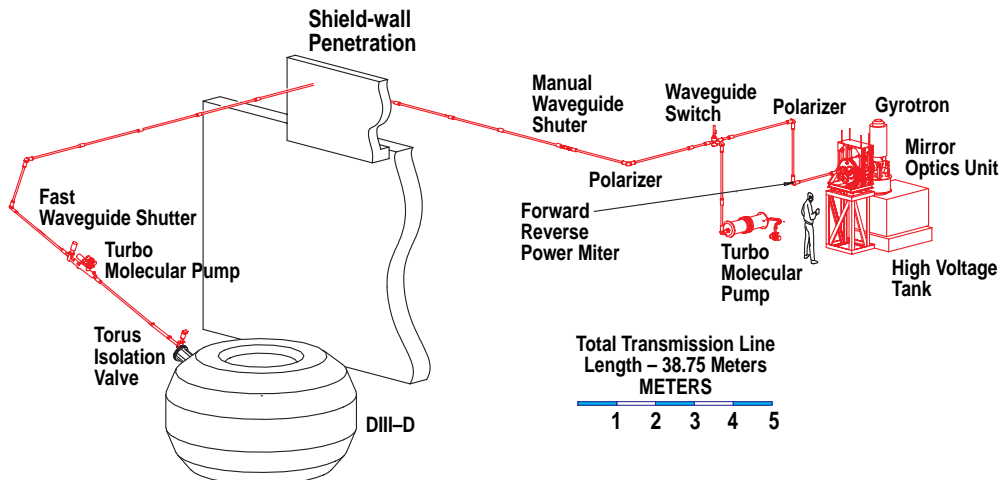


Fig. 2. ECH System layout showing the routing of the transmission line and the location of the major transmission line components.

waveguide and, in conjunction with the pumping section, maintains the vacuum pressure at the tokamak entrance waveguide long enough for the torus isolation valve to close ≈ 0.8 – 1 s.

To aide in gyrotron optimization a dummy load is connected to the system via a waveguide switch located near the gyrotron. Polarization control is achieved by a set of grooved polarizing mirrors mounted in two of the mitre bends. By appropriate rotation of these two mirrors, any elliptical polarization desired can be obtained.

Inside the tokamak are two mirrors, a focusing mirror and a flat turning mirror, permanently angled at 19° off normal to provide the appropriate current drive injection. The tilting mirror rotates vertically so the injected beam can be steered poloidally from slightly below the midplane of the plasma, to the outermost top edge of the plasma.

INITIAL OPERATION INTO DIII-D

An important issue for the usefulness of the ECH system is the validation of the spot size that interacts with the plasma. The launcher was designed to inject the rf beam 19° off-normal to drive current, and analysis of the launcher optics predicts that 98% of the rf power will be in an area with a diameter of 19.7 cm at the plasma center. The full width half maximum (FWHM) value for a Gaussian beam with a 19.7 cm 98% power spot size is 8.3 cm. The actual power deposition profile was measured from IR images of the rf beam impinging on a paper target placed inside the DIII-D vacuum vessel at the plasma center location. These measurements are summarized in Fig. 3, where the power deposition profile is seen to match the expected Gaussian profile except for a low level wing, which may indicate the presence of some higher order modes.

One of the other useful applications of ECH is the determination of the localized thermal transport coefficient. To perform this task the rf power is modulated at a relatively high rate. This is simply achieved by modulating the gyrotron voltage (by only 16%) for the GYCOM gyrotron and by turning on and off the mod-anode on the CPI gyrotron. Modulation frequencies as high as 1 kHz have been tested, Fig. 4 shows a typical response of the central electron temperature as measured by the electron cyclotron emission (ECE) diagnostic.

Injection of approximately 500 kW into low density plasmas has resulted in central electron temperatures as high as 12 keV. Traces of a discharge with a peak electron temperature of 10 keV is shown in Fig. 5 along with the electron profile determined from the Michelson interferometer, the heterodyne radiometer and Thomson scattering.

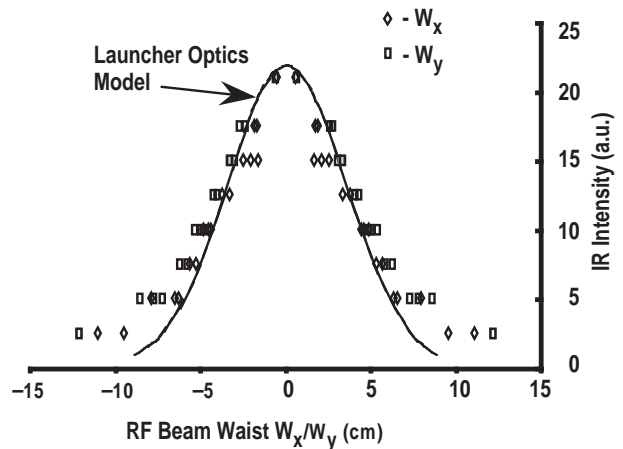


Fig. 3. Power deposition profile measured from IR camera images of the rf beam striking a paper target placed at the center of the DIII-D vacuum vessel. The Gaussian profile developed from the launcher optics is also shown.

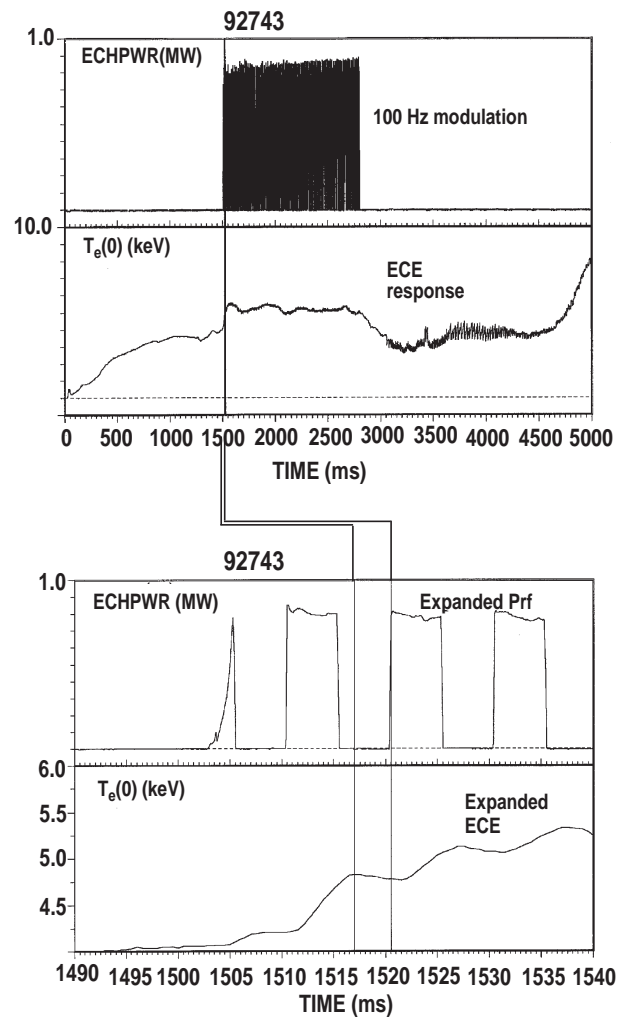


Fig. 4. Central electron temperature as measured by the electron cyclotron emission (ECE) diagnostic for a plasma heated with modulated ECH, modulation frequency ≈ 100 Hz. Gyrotron power was ≈ 850 kW.

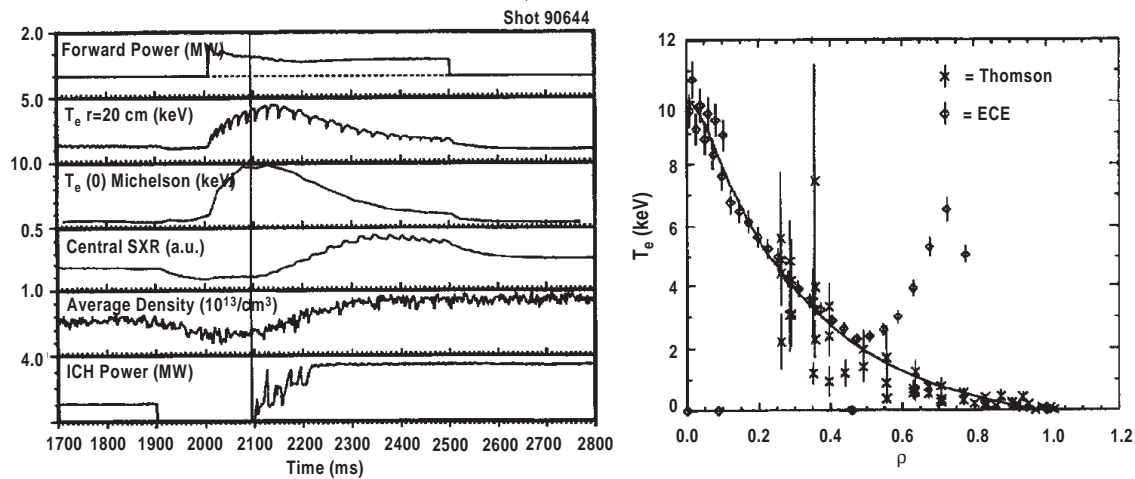


Fig. 5. (a) time dependence of the forward rf power and several diagnostic traces during ECH heated plasmas: (b) the electron temperature profile from ECE and Thomson scattering at the time shown by the vertical line on the time plots.

CONCLUSION

The first of three MW ECH systems is operating routinely at DIII-D with generated power at 110 GHz of approximately 900 kW, pulse lengths up to 2 s and good power accountability. Initial rf power injection into DIII-D plasmas has been performed for 2 s both unmodulated and modulated. The MHD measurements of the plasma energy increase indicates that about 550 kW was absorbed for 800 kW generated. Initial transport experiments using modulated ECH have been performed as well as combined ECH and ICRF fast wave current drive experiments.

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