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Abstract: The 110 GHz system on the DIII-D tokamak comprises three Gycom Centaur class gyrotrons producing 750 kW for 2.0 sec pulses and one CPI VGT8110 series gyrotron producing 800 kW for 2.0 ec pulses. Total injected power is in excess of 2 MW. An additional two CPI gyrotrons are being prepared for operation following failure of their diamond output windows and these failures have resulted in operational limits on power and pulse length for the operating CPI gyrotron. The system has poloidally steerable launchers for four gyrotrons, two with oblique launch for current drive and two with perpendicular launch for heating only. A fully articulating launcher with poloidal scan and ±19 deg toroidal scan is also operational. Radiatively cooled mirrors capable of 1 MW for 10 s pulses at 1% duty cycle are being tested on the oblique launcher. New dummy loads based on conversion of the $HE_{1,1}$ fundamental mode to surface modes and having fast time response and 80% absorption of the incident rf are now in service. A new single mirror coupling scheme for the diamond window gyrotrons has cut losses in the wave coupling process in half to about 6% of the generated power for focused Gaussian beams. The evacuated windowless waveguide lines are up to 100 m in length and are greater than 90% efficient. The performance of the dummy loads, output power modulation, polarization control and the transmission line will be presented. The history and analysis of the failures of the diamond windows will also be discussed.

SYSTEM DESCRIPTION

The DIII-D ECH system now consists of four gyrotrons, each of which generates in excess of 700 kW at 110 GHz, plus beam correction and focusing optics, transmission lines, dummy loads, polarization controls and launchers. Power injected into the DIII–D tokamak is in excess of 2.0 MW and pulse lengths, which are limited in each case by the capabilities of the gyrotron output windows, are up to 2.0 s. The system in its present configuration is shown in Fig. 1. Three of the gyrotrons, using BN output windows, were manufactured by Gycom [1] and one, with an artificially produced diamond disk output window, was manufactured by CPI [2].

The evacuated transmission lines [3] are up to 100 m in length and are up to 85% efficient in the best and about 70% in the worst case. In order to pass safely through the BN output windows, which absorb about 4% of the incident rf power, the rf beam in the Gycom gyrotrons was intentionally broadened. In order then to couple to the $HE_{1,1}$ fundamental circular waveguide mode, the rf beam from these gyrotrons had to be phase corrected and focused at the waveguide input. This is done with a system of two

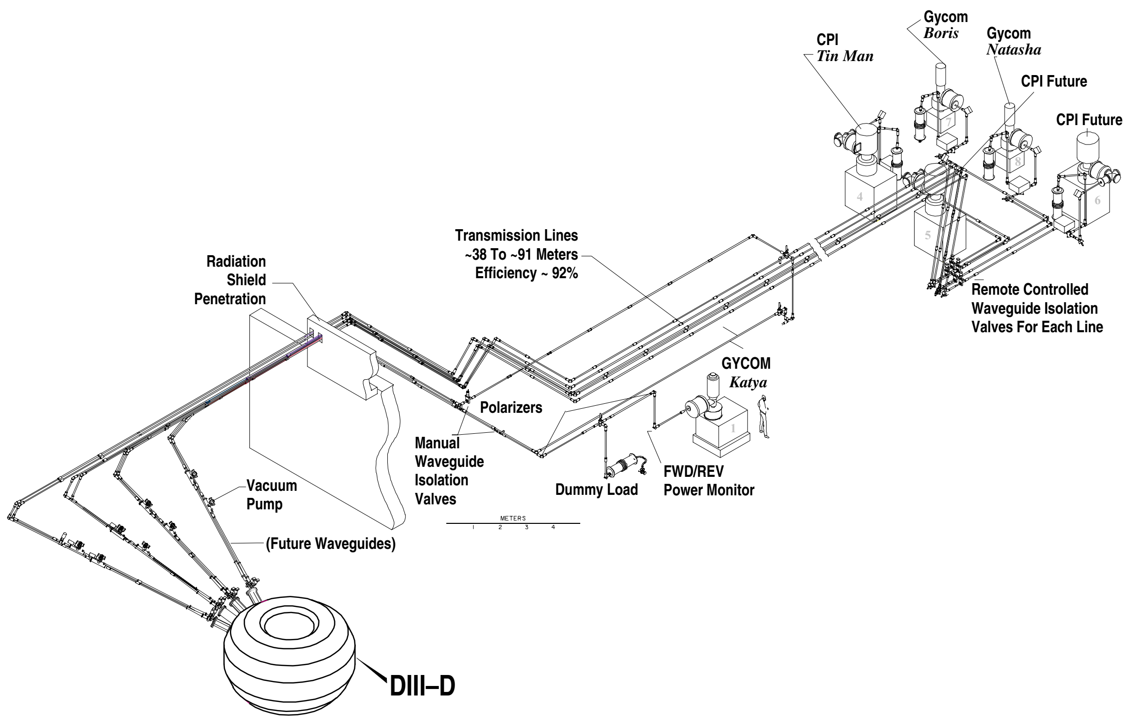

FIGURE 1. Isometric view of the gyrotron installation on the DIII–D tokamak. The lines are grouped in pairs at the tokamak. Each line includes dummy load, polarizer pair, power monitor, isolation valve, and pumping system.

mirrors, the surfaces of which were calculated from phase retrieval calculations using beam profile measurements on the free space propagating beam. The low loss and high thermal conductivity of the diamond window permits the CPI gyrotron to produce a Gaussian beam directly and this beam can be focused to a waist at the waveguide input using a single ellipsoidal mirror with about 94% efficiency compared with about 84% for the phase correcting two mirror system. The two coupling schemes are compared in Fig 2. The transmission lines are windowless and the waveguide pressure near the tokamak is less than 1×10^{-6} Torr. Polarization control is provided by pairs of sinusoidally grooved mirrors in miter bends.

Each system is equipped with a dummy load capable of handling 1 MW for up to 1.0 s. The loads are inconel cylinders with stainless steel water jackets. It was necessary to improve the long pulse power handling capability of these loads, so a second load is being installed on each of the waveguide lines in front of the inconel loads. These new loads, which operate on the principle of mode conversion in smooth wall waveguide [4], are Glidcop with a stainless steel water jacket carrying about 240 ℓ/min cooling water flow and include a waveguide bellows to compensate for the thermal expansion of the copper. The mode conversion loads absorb about 75% of the incident power and have the additional advantages that the thermal time response for calorimetry is greatly reduced. The combination of the two loads in series is as black as the plasma from the standpoint of reflected power and should operate cw at 1 MW absorbed power.

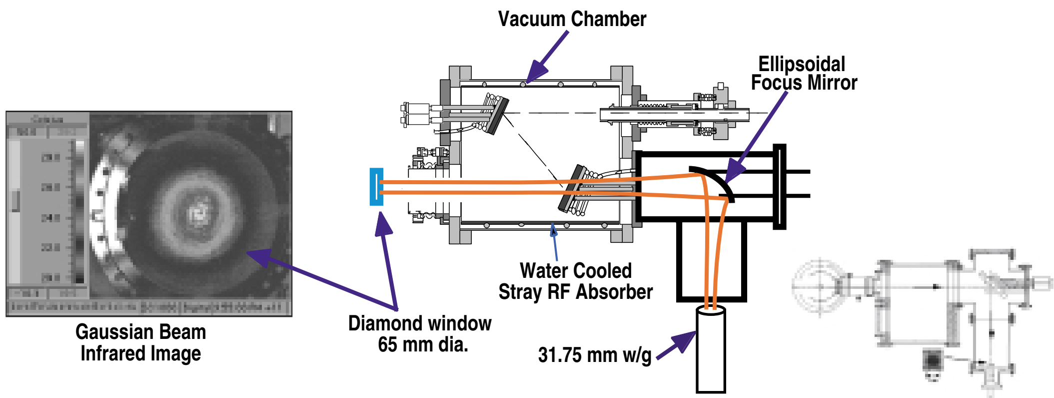

FIGURE 2. Waveguide coupling schemes with phase correction using a two mirror system for non-Gaussian beams and with no phase correction using a single mirror for Gaussian beams have both been used. The losses with the single mirror system are less than half those for the two mirror system. The figure shows the beam trajectory for the single mirror configuration superimposed on the two mirror arrangement.

OPERATIONAL EXPERIENCE

The gyrotron system itself has been very reliable and all the gyrotrons operate with rf generation efficiencies between 30% and 35%. Both modulated and unmodulated injection had been used at pulse lengths up to 2.0 s. Although modulation frequencies up to 20 kHz have been demonstrated, square modulation envelopes at 100% modulation depth have only been demonstrated up to about 1 kHz. In practice it is rare to modulate faster than about 300 Hz due to the poor signal/noise ratio for the tokamak diagnostics for rf pulses with low total energy. The control system supplies an analog signal to the high voltage modulator/regulator to modulate the output rf. About 15%–20% decrease in the high voltage supplied to the gyrotrons is sufficient to turn off the rf output. The electron beam is not cut off during modulation, so changes in the internal electrodynamics are kept to a minimum during the separate modulated pulses and the gyrotron operation is quite stable.

Artificially produced diamond windows are being introduced on gyrotrons. These windows have thermal conductivity about four times greater than copper and, for the $2\lambda/2$ thickness used in the new group of CPI gyrotrons, absorb about 0.2% of the transmitted power.

The earliest CVD diamond windows placed in service used an aluminum diffusion bond and were edge cooled by water in contact with the diamond material. Despite the use of anti-corrosive additives in the water, corrosion of the window seals was a problem, which led to the failure of the window on the first test and development gyrotron installed at DIII–D. A new braze technique using Au/Cu material has been developed at CPI and is being used in place of the aluminum bond technique. In addition to leaks in the seals, another window failed due to excessive microwave absorption which was believed to have arisen from a thin lossy layer on the surfaces of the diamond, which apparently formed during the braze process. These layers can easily be removed by proper mechanical etching.

CONCLUSION

The high power gyrotron system on DIII–D now is reliably injecting over 2.0 MW for up to 2.0 second pulses. Both current drive and heating/transport experiments have been performed. Two additional gyrotrons will be available during the 2002 experimental campaign.

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