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GENERAL ATOMICS

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ABSTRACT

A 110 GHz gyrotron designed for long pulse operation at $P_{rf} > 1.0$ MW will be tested at the DIII–D facility. The unit is predicted to have efficiency > 0.4 with collector potential depression. Some transmission line components require modification for operation at total rf energies > 5 MJ per pulse. The ECH system is also being upgraded with the addition of three new gyrotrons.

1. INTRODUCTION

A new prototype 110 GHz gyrotron with collector potential depression [1] and nominal output power >1.0 MW has been designed by the U.S. gyrotron development program and is presently in the final stages of construction at Communications and Power Industries (CPI). Although the tube represents an evolutionary rather than radical increase in performance compared with the 1 MW gyrotrons currently operating at the DIII–D tokamak, it nevertheless could result in substantial long term cost savings, if the predicted performance is realized, by reduction of the number of gyrotrons eventually required to achieve DIII–D program requirements. In parallel, the DIII–D gyrotron complex will be adding three long pulse gyrotrons in the 1 MW class during 2005.

2. DEPRESSED COLLECTOR GYROTRON

The new gyrotron represents an attempt to achieve maximum performance from a design for gyrotrons which have performed well as research tools, routinely generating about 900 kW for ≤ 5 s pulse lengths with a variety of modulation and control scenarios in a large system [2]. The depressed collector gyrotron will operate at a total voltage drop of 96 kV, with 25 kV collector depression and 40 A beam current. In addition to collector depression, the tube exhibits several changes from the earlier 1.0 MW designs. Although the present designs use a coaxial collector with shielding for magnetic field control, the new tube will have a cylindrical collector of smaller diameter with strong sweeping, which should keep the peak collector power loading $\lesssim 600$ W/cm^2 and which greatly simplifies the collector assembly. This cylindrical collector is made possible by the higher efficiency of the depressed collector geometry, which is predicted to be > 40%.

Additional changes in the design have been made. Because of the extremely long time required to condition the present gyrotrons to maximum parameters of 1.0 MW and ≥ 5.0 s pulse length (approximately 60 days of around the clock operation), improved ion pumping has been provided. In the coaxial collectors, all ion pumping was done through the center coaxial section of the collector with two 75 l/s ion pumps. In the new design, these ion pumps have been moved to the mirror box near the output window. This eliminates pumping through the electron beam, which is believed to be inefficient during the gyrotron pulse owing to ionization of the neutral gas by the beam. The clear aperture of the CVD diamond window has been increased to 77 mm from 51 mm in the present design. Only subtle changes in the cavity/launcher designs have been made, in part to fill the larger output window, but these changes also promise to yield an increase in the efficiency of production of a Gaussian beam [3]. The excited mode is still the $\mathrm{TEM}_{22,6,1}$ cavity mode. Cavity loading is <1.5 kW/cm^2.

The long term plan is to test the gyrotron to full power for short pulses and approximately half power for long pulses at CPI and then test to full parameters at General Atomics. The tube will then be used in the fusion research program at the DIII–D tokamak to gain operational experience before it is rebuilt with a two-stage depressed collector under development by Calabazas Creek Research, the University of Maryland and CPI. In Fig. 1, outline drawings of the single-stage depressed collector gyrotron and the proposed two-stage depressed collector modification are shown. In short-pulse testing at MIT, the gun and modified cavity generated ~1.4 MW at 96 kV, 40 A and 37% efficiency [4].

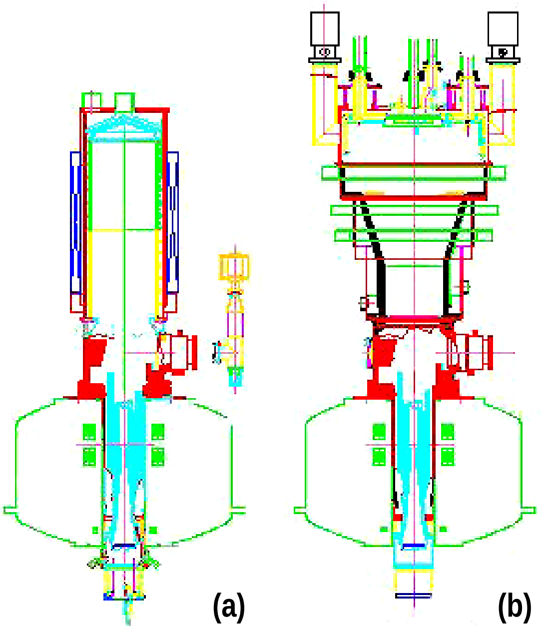

Fig. 1. The prototype single-stage depressed collector gyrotron design (a) and the planned subsequent modification to a two-stage depressed collector design (b).

3. DIII–D SYSTEM MODIFICATIONS FOR 1.5 MW

A DIII–D gyrotron system comprises the gyrotron; a Matching Optics Unit (MOU); dummy load; an evacuated transmission line incorporating grooved polarizing miter bends, power monitor miter bends and up to 10 weakly focusing miter bends; a waveguide switch; waveguide pumpout section; isolation valves; a transmitted power monitor and an articulating launcher. Each of these components has been examined to determine its suitability for operation at power levels up to 1.5 MW for up to 10 s pulse length at 1% duty cycle.

Although the circular corrugated aluminum waveguides employed in the DIII–D system are only 31.75 mm diameter, they exhibit extremely low loss in the $HE_{1,1}$ mode, about 0.5 dB per 100 m length. The operating pressure is $<10^{-6}$ Torr and only a few high energy pulses are required to condition the lines for full parameter operation. With the exception of the first few miter bends and the first few meters of waveguide, where high order modes arising from slight misalignment of the coupled rf beam have caused some arc damage, no evidence of arcing has been seen in the lines. The water-cooled normal miter bends and power monitor miter bends for the prototype gyrotron line are being modified to bring the water closer to the reflecting surface and Glidcop is being used for these mirrors. The waveguide layout is also designed so that, to the maximum extent possible, the wave is polarized with the electric field perpendicular to the plane of the bend, which has about half the loss of the orthogonal polarization.

A waveguide switch is used to route the rf either to the tokamak, in which case it looks like waveguide, or to the dummy load, in which case it serves as a miter bend. Cooling for the mirror in the dummy load position is provided by contact pressure against the cooled body of the switch, which is relatively inefficient. The switch is being oriented so the wave polarization will be in the low loss direction, and no other changes are being made.

The present dummy load configuration has a waveguide mode conversion dummy load [5] backed by an Inconel dummy load. This combination is marginal for 1.5 MW, 10 s pulses, therefore a second mode conversion load is being inserted in series. This scheme relies on the experimental observation that the rf power not absorbed in the first waveguide load exits the load primarily in the $HE_{1,1}$ waveguide mode, so a second similar load can be added in series. The Inconel backstop load is being replaced by an aluminum tank load, which can be installed under the raised floor in the gyrotron hall. The first mode conversion load is being designed to reduce the power by 3 dB and the second series load will absorb 10 dB, leaving about 75 kW to be absorbed in the aluminum load.

DIII–D site regulations require a 30 kV dc isolator in each of the ECH waveguide lines. The gap in these isolators radiates about 0.14% of the waveguide power into the alumina ceramic forming the main structure, which in turn absorbs about 40% of the incident power. This can cause a 100°C gradient across the ceramic, producing a stress about 50% of the fracture stress for a full parameter pulse into the tokamak. This component will be closely monitored during initial high power operation.

The rf is launched into the DIII–D vacuum vessel after reflection from a fixed weakly focusing mirror and a flat articulating steering mirror. These mirrors are cooled by radiation to the port box and limited conduction. Studies of the thermal performance of the mirrors have been performed under operational conditions [5]. After about 8 h of plasma experiments in which a 2 s pulse delivering 700 kW to the plasma was fired every 17 minutes, the steering mirror temperature plateaued at about 60°C above ambient. Approximately half of this increase was due to heating of the launcher and surroundings by plasma radiation at high beta. For injected ECH power of 1 MW, it is unlikely that the mirror temperatures will reach dangerous levels, particularly since the radiative cooling is proportional to T^4. Model calculations of the peak surface temperature are still in progress for these launcher mirrors, but calculations of the peak surface temperature of the aluminum mirrors in the MOU showed a maximum temperature increase of 92 K for 1.5 MW applied for 10 s with no cooling, so it is likely that no protective action will need to be taken for the copper launcher mirrors even if the power density is twice that for the MOU mirror. The MOU mirror calculations are summarized in Fig. 2.

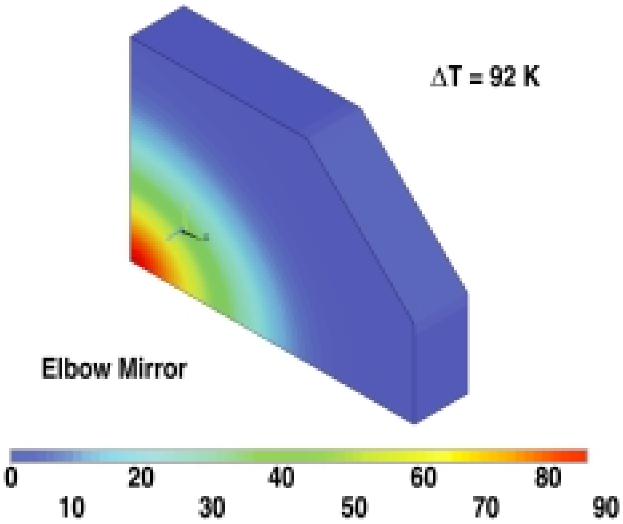

Fig. 2. Thermal loading calculations for an uncooled aluminum mirror at 45 deg incidence to a 1.5 MW rf beam with Gaussian profile applied for 10 s. The temperatures are in degrees Kelvin.

4. SYSTEM STATUS

In parallel with these activities, the DIII–D program is adding three gyrotrons in the 1.0 MW, 5 s class, bringing the total of these tubes to six. Including the 1.5 MW prototype and the short pulse Gycom gyrotrons, the system will comprise six active gyrotrons and two available spares. Addition of two more transmission lines to bring a total of eight tubes on line is being evaluated. At present, three CPI and two Gycom gyrotrons are in routine experimental service.

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