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Recent Tests on 117.5 GHz and 170 GHz Gyrotrons

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Abstract. Two megawatt-class gyrotrons at frequencies of 117.5 GHz and 170 GHz have recently been fabricated and tested at CPI. The 117.5 GHz gyrotron was designed to produce up to 1.8 MW for 10-second pulses, and will be used for electron cyclotron heating and current drive on the DIII-D tokamak at General Atomics. The 170 GHz gyrotron is specified as a 500 kW CW system, but has been designed with the goal of generating up to 1 MW CW. Oak Ridge National Laboratory will use the gyrotron in ITER ECH transmission line testing.

1 Introduction

Gyrotrons capable of generating 1-2 MW at mm-wave frequencies are a key technology for large-scale magnetically confined fusion experiments, which rely on localized electron cyclotron heating for plasma heating, current profile control, and suppression of potentially disruptive plasma instabilities. Gyrotrons make use of the cyclotron resonance maser instability to convert the power flowing through a DC electron beam into a radiated Gaussian output beam at the desired resonant frequency. Several gyrotron developers have constructed devices producing continuous output power levels of 1 MW or more, for frequencies as high as 170 GHz, and efforts to develop gyrotrons capable of reliably generating 2 MW are in progress at several sites.

This paper summarizes the design and initial test results on two of CPI's most recent gyrotron designs. At a frequency of 117.5 GHz, a gyrotron designed to produce 1.5 to 1.8 MW of output power, for pulse lengths up to 10 seconds, has been fabricated and tested. The gyrotron was developed specifically for use in plasma heating and current drive experiments on the DIII-D tokamak at General Atomics. At 170 GHz, CPI's prototype gyrotron has been rebuilt to address deficiencies observed in initial tests. This gyrotron, which is to be used for transmission line component testing by the US ITER program, is specified as a 500 kW CW device, but is designed to produce 1 MW CW.

2 117.5 GHz Gyrotron

2.1 Design of 117.5 GHz gyrotron

The 117.5 GHz gyrotron is designed to produce output power levels up to 1.8 MW for 10-second pulses when operating with an accelerating voltage up to 105 kV and a beam current of 60 A. The device is also designed to produce 1.5 MW output power at beam currents up to 50 A. This gyrotron employs a depressed collector, a diode magnetron injection electron gun, a cylindrical interaction cavity in which the $TE_{20,9,1}$ mode is excited, and an internal converter to transform the excited mode into a high-quality fundamental Gaussian output beam, which exits the gyrotron horizontally through a CVD diamond output window. The collector is constructed from a strengthened copper alloy to mitigate the effects of cyclic fatigue. A schematic diagram of the gyrotron is shown in Figure 1.

2.2 Test results on 117.5 GHz gyrotron

In Figure 2 we show a photograph of the 117.5 GHz gyrotron after installation into the test enclosure. In initial testing on the 117.5 GHz gyrotron all performance goals except for the ability to operate at extended pulse lengths were achieved. The short-pulse (~5 ms) tests demonstrated output power levels up to 1.8 MW (for a beam current of 60 A, an accelerating voltage of 98 kV, and a collector depression voltage of 25 kV). Output power levels up to 1.5 MW were obtained with a beam current of 50 A. A plot of output power and efficiency versus beam current is shown in Figure 3. Operation in the desired mode was observed over a broad range of operating parameters with little evidence of mode competition. Internal diffraction losses were measured calorimetrically to be about 3.5% of the total output power. Cavity power losses were as predicted, and no excess power was absorbed in the beam tunnel. Collector power distribution measurements using external temperature sensors confirmed that the spent electron beam power was spread over a broad range of the

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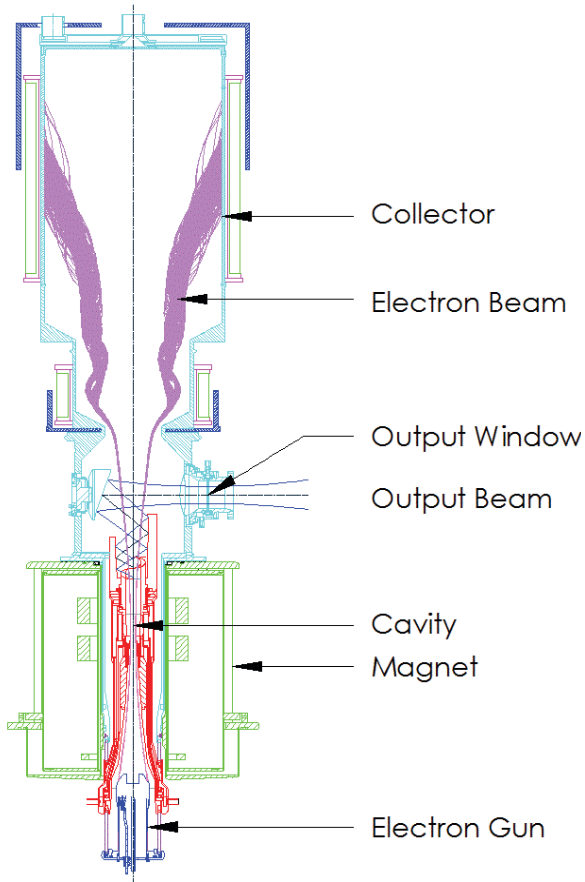

Figure 1. Schematic diagram of 117.5 GHz gyrotron and superconducting magnet.

Figure 2. Photograph of 117.5 GHz gyrotron and superconducting magnet installed in test enclosure at CPI.

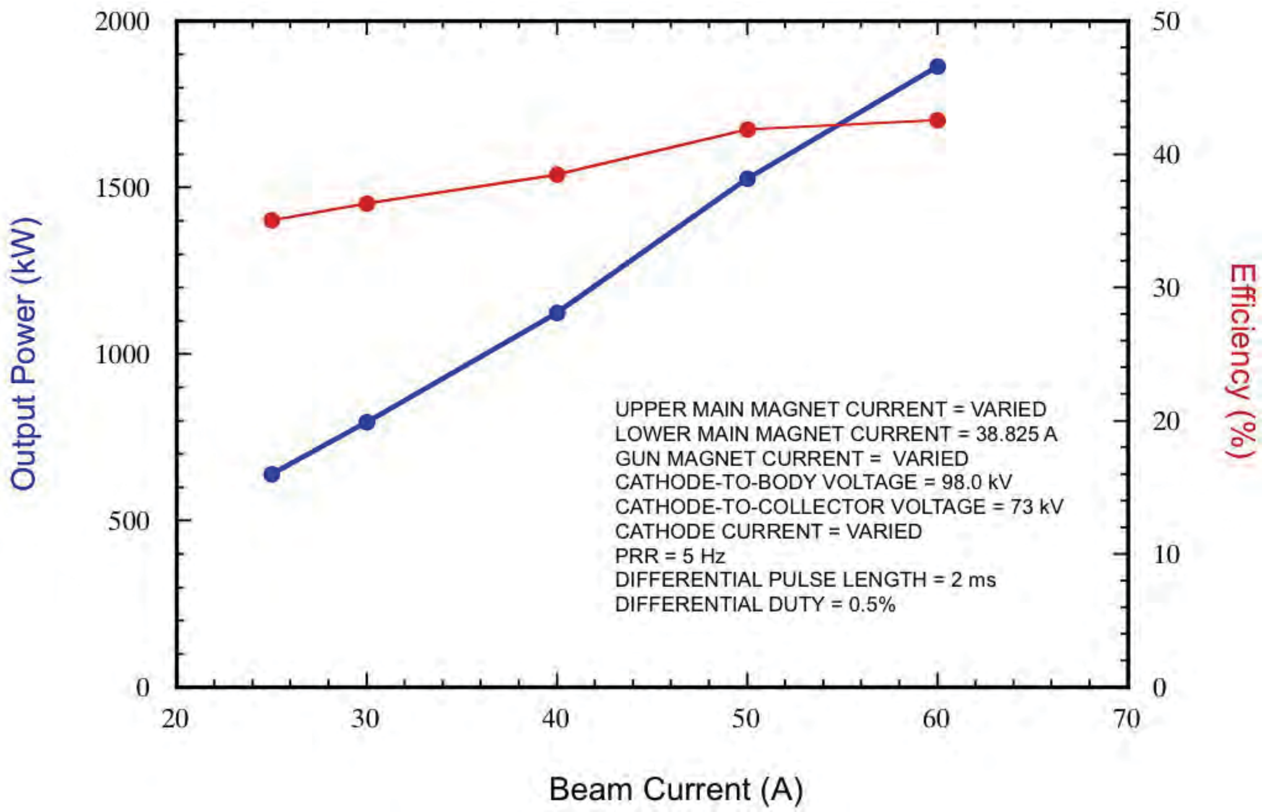

Figure 3. Output power and efficiency versus beam current for the 117.5 GHz gyrotron.

collector surface, and that the peak time-averaged power densities were within acceptable limits. Thermal imaging of the output beam confirmed the proper operation of the internal converter, consistent with cold-test measurements that were performed prior to completion of gyrotron assembly. In Figure 4 we show thermal images of the output beam at a position of 43 cm from the output window flange. In Figure 5, we show horizontal and vertical cross sections of the image shown in Figure 4.

Work is currently underway to improve the long-pulse performance of the gyrotron.

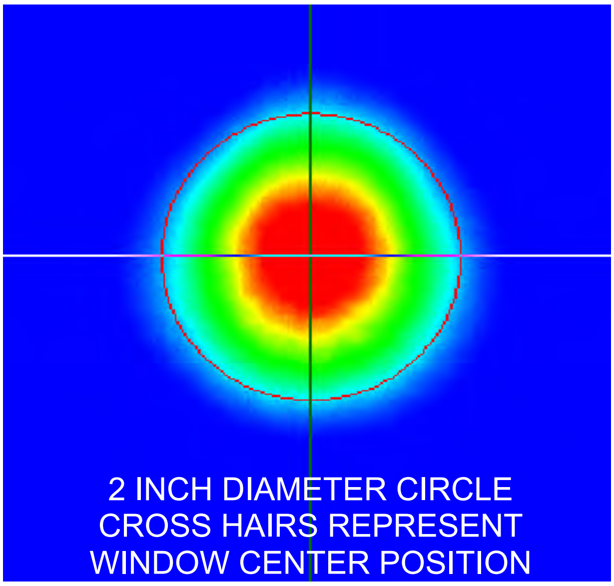

Figure 4. Thermal image of the output beam at a position of 43 cm from the output window flange.

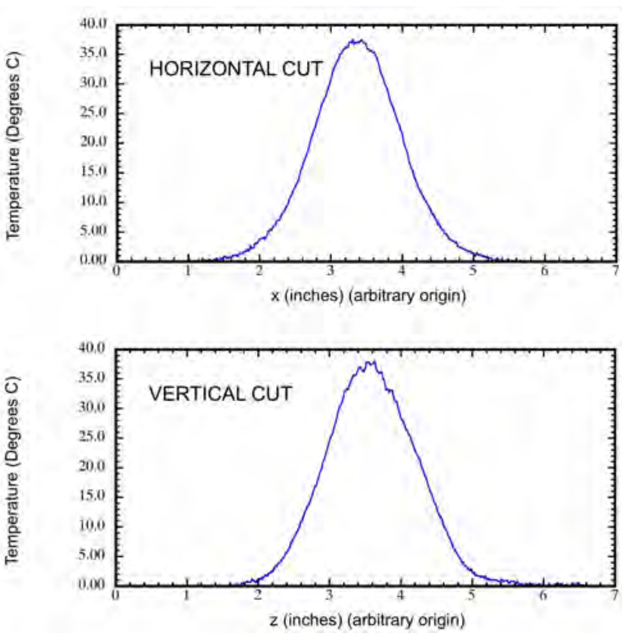

Figure 5. Horizontal and vertical cross sections of the thermal image of the output beam shown in Figure 4.

3 170 GHz Gyrotron

3.1 Design of 170 GHz gyrotron

The 170 GHz gyrotron is specified to produce 500 kW CW but has been designed for operation up to 1 MW CW. The nominal design point for generating 1 MW of output power is an accelerating voltage of 75 kV (80 kV max) and a beam current of 45 A (50 A max). A depressed collector, with a nominal depression voltage of 27 kV (30 kV max) is employed. An edge-cooled CVD diamond output window is used to transmit the gyrotron's Gaussian output beam with minimal loss. The electron beam produced by the electron gun interacts with the $TE_{31,8,1}$ mode of the interaction cavity, and this mode is converted to a Gaussian output beam using an internal converter consisting of a dimpled-wall launcher and three phase-correcting mirrors. Like the 117.5 GHz gyrotron, the 170 GHz gyrotron collector employs a strengthened copper alloy, as well as iron beam shaping and active magnetic sweeping to reduce both instantaneous and time-averaged power densities to levels compatible with long life. In Figure 6 we show a layout diagram for the 170 GHz gyrotron.

3.2 Test results on 170 GHz gyrotron

A photograph of the 170 GHz gyrotron is shown in Figure 7. In the first series of tests several factors hampered the ability to achieve operation at the intended high-efficiency region of parameter space. Access to the highest-efficiency operating regime was limited by mode competition, which was determined to be a result of the mod-anode gun startup scenario. In addition, operation at the lower magnetic fields expected to yield the highest efficiency also resulted in sporadic mod-anode current, and the presence of even very low levels of mod-anode current prevented long-pulse operation from being reliably achievable. Finally, absorption of power in the beam tunnel was found to increase with operating voltage, indicating that the absorbing material in the beam tunnel was not sufficient to prevent the excitation of unwanted beam tunnel oscillations. As a result of these various factors, the maximum output power achieved during initial tests was limited to 600 kW for short pulses and 300 kW for long (15 second) pulses.

Following the first test sequence, the gyrotron was rebuilt with a diode electron gun to replace the mod-anode gun and a new beam tunnel to inhibit the observed beam tunnel oscillations. The gyrotron is now undergoing a second series of tests with the rebuilt configuration. In initial short-pulse testing, output power levels of 1 MW have been achieved with an accelerating voltage of 79.4 kV and a beam current of 50 A. The specified 500 kW output power level was achieved with an accelerating voltage of 78 kV and a beam current of 25 A. The collector depression voltage was 20 kV in both cases. A plot of output power and efficiency versus beam current for a cathode-to-body voltage of 75 kV is shown in Figure 8. Long-pulse tests are underway.

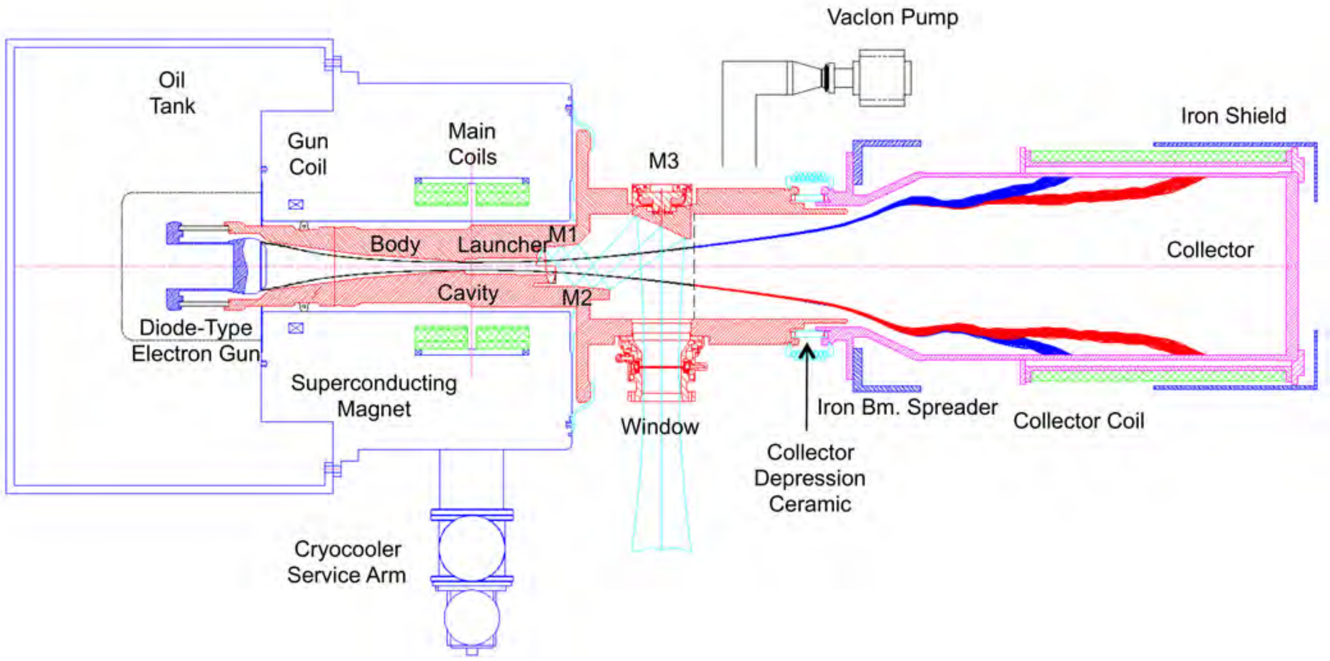

Figure 6. Schematic diagram of 170 GHz gyrotron and superconducting magnet.

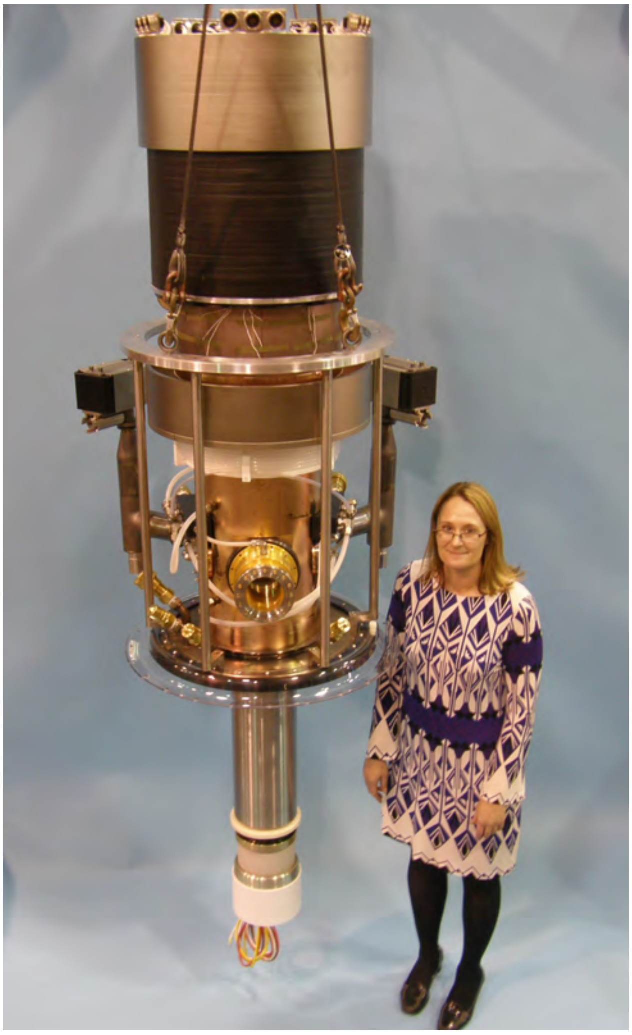

Figure 7. Photograph of 170 GHz gyrotron.

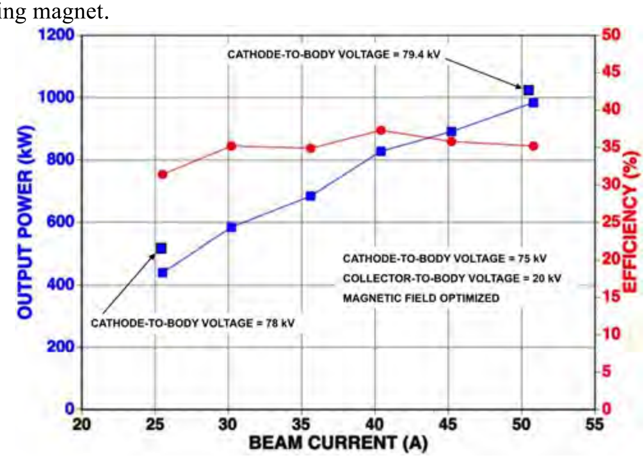

Figure 8. Output power and efficiency versus beam current for a cathode-to-body voltage of 75 kV. Also shown are higher-power points near 25 A and 50 A beam current that are obtained with higher cathode-to-body voltage.

4 Conclusions

High-power gyrotrons for magnetic fusion applications at frequencies of 117.5 GHz and 170 GHz have been fabricated and tested. The 117.5 GHz gyrotron achieved an output power of 1.8 MW at a beam current of 60 A during short-pulse testing. Long-pulse tests were inhibited by high-voltage problems and are currently being addressed in order to satisfy the 10-s pulse length requirement for the gyrotron. The 170 GHz gyrotron was rebuilt with a diode-type electron gun instead of the original mod-anode-style gun and was able to achieve 1 MW output power in short-pulse tests. Long-pulse testing on this gyrotron is currently in progress.