Recent ITER-Relevant Gyrotron Tests

K. Felch, M. Blank, P. Borchard, P. Cahalan, S. Cauffman, T.S. Chu, and H. Jory
Communications and Power Industries, 811 Hansen Way, Palo Alto, CA, 94303, USA
E-mail: kevin.felch@cpii.com

Abstract. Recent tests of two different megawatt-class gyrotrons at CPI provide a design baseline for the 120 GHz, 1 MW CW gyrotrons required by ITER for plasma start-up. The two gyrotron designs include a 140 GHz, 900 kW CW device that was delivered to the Max Planck Institute for Plasma Physics in Greifswald, Germany, and a 110 GHz, 1.3 MW CW gyrotron that was recently tested at CPI. Both gyrotrons utilize many of the same features that are foreseen for the ITER 120 GHz gyrotrons. These features include: single-anode magnetron injection electron guns, high-efficiency internal converters that produce a pure TEM$_{00}$ output mode, 88-mm-diameter diamond output windows and single-stage depressed collectors. In tests at CPI, the 140 GHz gyrotron achieved 500 kW power levels for 700-s pulses and 930 kW for short pulses. Long-pulse tests of the gyrotron, at beam currents above the 25-A test-set limit at CPI, were performed in Greifswald and resulted in output power levels of up to 900 kW for 30-minute pulses. In short-pulse operation at CPI, the 110 GHz gyrotron has achieved power levels of 1.28 MW. In long-pulse tests of the gyrotron, power levels of 500 kW were obtained for 10-s pulses.

1. Introduction
Current gyrotron requirements for ITER involve devices capable of at least 1 MW power levels for pulse durations that range from a few seconds to greater than 1,000 seconds at frequencies of 120 GHz and 170 GHz. The United States is currently slated to provide the 120 GHz gyrotrons that will be utilized for plasma start-up applications on ITER. Recently, two CPI gyrotrons have undergone tests in regimes that are relevant to the ITER requirements at 120 GHz. In addition to similar output power level and frequency, both gyrotrons incorporate many design features that are envisioned for the ITER 120 GHz gyrotrons. The first of these gyrotrons is a 140 GHz, 900 kW gyrotron that was designed, fabricated, tested and shipped to the Max Planck Institute for Plasma Physics in Greifswald, Germany for use in electron cyclotron heating experiments on the new Wendelstein 7-X stellerator. This gyrotron had undergone initial testing at CPI in 2003, up to the 25-A limit of the CPI power supply. Recently, the tube was tested up to full operating parameters at the Greifswald facility. In section 2, we list the main design features of the 140 GHz gyrotron and summarize the results of the initial tests at CPI and the more recent tests at Greifswald.

The second ITER-relevant set of tests involved a 110 GHz gyrotron that has been developed as part of the U.S. Department of Energy’s Gyrotron Development Program that includes contributors from MIT, Univ. of Maryland, Univ of Wisconsin, General Atomics and Calabazas Creek Research. The design of the 110 GHz, 1.3 MW gyrotron evolved out of the original 110 GHz, 1 MW design that was developed in the 1990s by CPI and the U.S Department of Energy’s Gyrotron Development Program. The goals of the new gyrotron design were to implement several design enhancements over the
original 1 MW tube that would result in higher output power levels, higher overall efficiency and higher reliability at the 1 MW level. This gyrotron has recently undergone initial testing at CPI. In section 3, we describe the basic design features of the 110 GHz gyrotron and how the new design differs from the earlier 110 GHz design. We will also discuss the results of the initial tests at CPI.

In section 4, we discuss these two gyrotron designs and recent test results in relation to the requirements for the ITER 120 GHz gyrotrons and point out areas where further advances or improvements are required.

2. 140 GHz, 900 kW gyrotron
The detailed design and initial tests on the 140 GHz gyrotron have been discussed elsewhere [1] but are summarized below along with the main results of the recent tests in Greifswald.

2.1. 140 GHz, 900 kW gyrotron design
Key features of the 140 GHz gyrotron are shown in the schematic diagram in figure 1.

![Schematic diagram of 140 GHz gyrotron.](image)

Figure 1. Schematic diagram of 140 GHz gyrotron.
The single-anode, or diode, magnetron injection gun was designed to operate at a nominal accelerating voltage of 80 kV and a nominal beam current of 40 A. The average cathode radius is 5.64 cm and the average cathode loading, at 40 A beam current, is 2.3 A/cm². The electron gun was designed to operate with air insulation and was operated in air in the initial tests at CPI. In the recent tests in Greifswald, oil insulation was employed, which facilitated cooling of the collector-depression ceramic shown in figure 1.

The interaction cavity was designed to support the TE_{28,7,1} mode at 140 GHz. The cavity, which consists of an input taper, straight section and an output taper, was designed for a cold Q of 1200 and an output mode purity of 99.8%. The predicted peak power density in the cavity was 1.6 kW/cm². Multi-mode efficiency calculations were carried out with a self-consistent, time-dependent code [2]. These calculations indicated that, for a cathode voltage of 80 kV, a beam current of 40 A, and a perpendicular-to-parallel velocity ratio of 1.5, 1.2 MW would be generated in the cavity, resulting in 1 MW output power. DC space-charge depression, which is approximately 5.5 kV in the cavity, was included in the simulation. The total predicted efficiency, assuming a cathode-to-body voltage of 80 kV and a cathode-to-collector voltage of 60 kV, or 20 kV depression, was 41.7%.

The internal mode converter was designed to efficiently transform the TE_{28,7} mode produced in the cavity to a Gaussian beam that exits the gyrotron perpendicular to the axis. The converter consists of a rippled-wall launcher and three focusing and steering mirrors, designed to optimize the shape and mode purity of the Gaussian beam and to bring the waist into the proper position to exit through the output window. The calculated diffraction losses for the internal converter system were about 5%, including 0.6% predicted loss at the output window due to spillover. Cold tests were performed to align the mirrors and verify the properties of the output beam. The measured beam pattern near the position of the window is shown in figure 2. Although a circular Gaussian beam was predicted by the theory, the cold tests showed that the output beam was slightly elliptic, but that at least 99% of the power would be transmitted through the output window.

![Figure 2. Cold test measurement of output beam pattern near output window position.](image-url)
The output window consists of an edge-cooled CVD diamond disc. The clear aperture diameter of
the window is 88 mm and the thickness is 1.8 mm, which is two wavelengths in the material at 140
GHz. A high-temperature braze technique was used in the fabrication of the window assembly.
Detailed thermal-mechanical analyses indicated that the maximum tensile stress for 1 MW operation
was two to three times lower than the ultimate tensile strength of the diamond for the measured loss
tangent of $5 \times 10^{-5}$ for the final brazed window. A photograph of the brazed window is shown in
figure 3.

![Brazed CVD diamond window for 140 GHz gyrotron.](image)

Figure 3. Brazed CVD diamond window for 140 GHz gyrotron.

A single-stage, depressed collector (SSDC) is used for efficiency enhancement. Since the body
operates above ground potential, an additional insulator, the collector-depression ceramic shown in
figure 1, is required. The two collector coils shown in figure 1 are used to generate an axial magnetic
field to spread the spent beam in the collector. Both coils are driven with an AC current to sweep the
spent electron beam with time to reduce the average power level in the collector. These coils are
mounted close to the collector cylinder and are enclosed inside a magnetic shield. For the nominal
cathode-to-collector voltage and beam current, 60 kV and 40 A, respectively, the maximum power
density in the collector is predicted to be 650 W/cm$^2$.

The magnetic field for the gyrotron is generated by a superconducting magnet that has a warm-bore
diameter of 20.32-cm. The nominal axial magnetic field at the cathode is 0.18 T and the ratio of the
magnetic field at the cathode to the magnetic field in the interaction cavity is 29.5.

A photograph of the 140 GHz gyrotron is shown in figure 4.
2.2. 140 GHz, 900 kW gyrotron test results
The initial tests on the 140 GHz gyrotron that were performed at CPI have been discussed in detail elsewhere [1]. Peak power levels above 900 kW were achieved with efficiencies of 34%. However, it was not possible to reach the design power level of 1 MW. Reasons for this shortcoming are not yet understood but could involve electron beam quality or mode competition. Figure 5 shows a map of output power for varying gun coil current, which results in a variation in the perpendicular-to-parallel velocity ratio in the beam, and taper coil current, which varies the magnetic field in the interaction region. For each point on the curve, the cathode-to-body and cathode-to-collector voltages were held fixed at 80 kV and 60 kV, respectively. Although the filament power was held constant, the beam current varied from 43.2 – 45.1 A throughout the measurement. As seen in the figure, the maximum

Figure 4. Photograph of 140 GHz gyrotron.
output power was measured to be 923 kW, which corresponds to 34% efficiency. Due to power supply limitations at CPI, pulse lengths longer than a few milliseconds could not be achieved at beam currents greater than 25 A. Therefore, long-pulse demonstrations were carried out at the 500 kW output power level with 80 kV cathode-to-body voltage, 55 kV cathode-to-collector voltage, and 24.7 A beam current. The pulse length was extended to 700 seconds with very little difficulty. During the tests, numerous 600-second pulses were taken, including a sequence of ten in a row without a fault. Pulses longer than 700 seconds at the 500 kW output power level were not attempted due to heating in the collector depression ceramic (see figure 1) caused by stray RF power not directed through the output window by the internal converter system.

![Figure 5. Mode map showing parameters for maximum output power of 923 kW.](image)

The later addition of oil cooling for the tests in Greifswald enabled higher-power and longer-pulse operation. The tests in Greifswald were carried out by personnel from the Max Planck Institute for Plasma Physics with assistance from CPI. Following a series of initial activities to verify the correct operation of the gyrotron and superconducting magnet in the new power supply system at Greifswald, output power levels and pulse duration were both gradually increased. In March 2005, output power levels of 820 kW were measured in the final calorimetric load for the system for a continuous pulse duration of 30 minutes. Since it is estimated that about 10% of the output power from the gyrotron is not captured in the dummy load due to a number of factors, the gyrotron output power was about 900 kW. Parameters for the 30-minute pulse were: collector voltage = 55 kV, body voltage = 25 kV, beam current = 45 A and body current = 26 mA. In figure 6, a plot of the vac-ion current, which is a measure of the internal vacuum pressure, is shown over the duration of the 30-minute pulse. The increase in current (vacuum pressure) at the end of the pulse is due to the pumping effects of the electron beam. Output power as measured in the final calorimetric load over the duration of an earlier 27-minute pulse is shown in figure 7. Two 2-minute pulses precede the 27-minute pulse.
Operation of the gyrotron appeared to be quite stable over the long pulse durations, validating the basic CW design of the gyrotron. Unfortunately, a vacuum leak developed in subsequent testing so it is possible that some portion of the tube was damaged in the long-pulse testing. The specific cause of the leak has not yet been determined but will be investigated in coming months.

3. 110 GHz, 1.3 MW gyrotron
In many respects, the design of the 1.3 MW, 110 GHz gyrotron is similar to that of the 1 MW device previously developed and demonstrated by CPI [3]. Many aspects of the physics design have been investigated in recent tests at MIT [4]. Below we summarize the design and initial test results on the gyrotron.

3.1. 110 GHz, 1.3 MW gyrotron design
A schematic diagram of the 110 GHz, 1.3 MW gyrotron and magnet is shown in Figure 8. Although the optics and high-voltage designs of the electron gun for the higher-power gyrotron have been altered for operation at a beam voltage of 96 kV (up from 80 kV for the 1 MW design) and beam
current of 40 A, the single-anode gun makes use of the same size cathode as that employed in the 1 MW device. As with the 1 MW gyrotron, the 1.3 MW design utilizes oil insulation in the electron gun region. The interaction cavities of both the 1 and 1.3 MW gyrotrons are designed to operate in the $\text{TE}_{22,6,1}$ mode, but the cavity has been modified to optimize the efficiency for an output power level of up to 1.5 MW, while keeping ohmic losses on the cavity walls at values that are consistent with standard cooling techniques.

Like the 110 GHz, 1 MW gyrotron, the internal converter for the 1.3 MW device consists of a rippled-wall launcher and four mirrors to convert the $\text{TE}_{22,6}$ mode produced in the cavity into a fundamental Gaussian mode at the output of the gyrotron. The CVD diamond output window for the 1.3 MW gyrotron has a clear aperture of 88 mm, which is somewhat larger than the 50.8-mm aperture of the earlier 110 GHz, 1 MW gyrotrons, but the same size as the aperture of the 140 GHz gyrotron. To accommodate the larger window, the internal converter mirrors have been changed to produce a larger output beam at the window. The collector design has been modified in two ways from that of the 110 GHz, 1 MW gyrotrons. First, for the 1.3 MW gyrotron, collector depression is employed to reduce the amount of power that must be dissipated in the collector and also to increase the overall device efficiency. A single-stage, depressed collector, with a configuration similar to the 140 GHz gyrotron, is employed. Nominally, the collector voltage would operate at 71 kV and the body voltage would be 25 kV to yield the full 96 kV accelerating or cathode-to-body voltage. A second departure from the 1 MW collector design involves the collector size and collector-coil geometry. The collector for the 1.3 MW gyrotron is significantly longer and somewhat smaller in diameter than that of the 1 MW gyrotron, and, thereby, easier to manufacture. While the 1 MW design employs a collector magnet coil near the entrance of the collector, the 1.3 MW design relies on a room-temperature coil that covers much of the collector length as well as iron shielding to tailor the magnetic field in the collector region. Both the 1 MW and 1.3 MW collector designs rely on modulation of the collector coil current to spread the distribution of the spent electron beam over the surface of the collector in the axial direction. A photograph of the 110 GHz gyrotron prior to bakeout processing (no collector coils or hardware attached) is shown in figure 9.
Figure 9. Photograph of 110 GHz, 1.3 MW gyrotron before bakeout processing.
3.2. 110 GHz, 1.3 MW gyrotron tests  
Initial tests were carried out under short-pulse conditions at CPI. The maximum output power observed in these tests was 1.28 MW with an efficiency of 42.3%. The collector voltage was 73.3 kV, the body voltage was 26 kV and the beam current was 41.2 A. At the nominal operating conditions, output power levels of 1.25 MW were obtained. In figure 10, we show a plot of output power and efficiency versus beam current for a collector voltage of 71 kV and a body voltage of 25 kV. Operation was possible over a wide range of body voltage values for a constant accelerating voltage. In figure 11, we show a plot of output power versus body voltage for a constant accelerating voltage of 95.5 kV and a beam current of 24.1 A.

![Figure 10](image1.png)  
**Figure 10.** Output power and efficiency versus beam current for the 110 GHz gyrotron.

![Figure 11](image2.png)  
**Figure 11.** Output power versus body voltage for a constant accelerating voltage of 95.5 kV.
Following short-pulse tests on the gyrotron, the tube was aged out to pulse durations of 10-s at the 25-A long-pulse, beam-current limit of the CPI power supply. Output power levels for long-pulse operation ranged from 500 kW to 520 kW for beam currents of 24 A-25 A. Collector and body voltages for the 10-s pulses were 73.5 kV and 20.9 kV, respectively. Future tests will be performed at General Atomics where increased power supply capabilities should enable operation up to the maximum output power levels of 1.2 MW-1.3 MW for 10-s pulses.

4. Discussion
The recent test results discussed above serve as an excellent basis for future 120 GHz gyrotrons for ITER. Design features incorporated in the two tubes, such as single-stage, depressed collectors, single-anode electron guns, use of high-order cavity modes, large-diameter diamond windows and efficient internal converters will be key features for the ITER gyrotrons. However, there are still areas where further work is necessary. First, overall gyrotron efficiency needs to be increased to values in excess of 50%. This will require improved interaction cavity designs and refinements to the depressed-collector approach. Obtaining greater than 50% efficiency will be complicated by the relatively low ITER collector voltage specification of 50 kV. Second, the ITER gyrotrons need to be highly reliable so that higher margins of safety may need to be considered in designing the key elements such as the collector, output cavity and output window. Finally, there will probably need to be improvements in interlock systems that protect the gyrotron and the dummy loads used to absorb and measure gyrotron output power, in addition to the many transmission line components that will need to handle CW power levels in excess of 1 MW.

Acknowledgements
We would like to acknowledge the members of the U.S. Department of Energy’s Gyrotron Development Program, including MIT, General Atomics, Univ. of Wisconsin, Univ. of Maryland and Calabazas Creek Research for their contributions to the design of the 110 GHz gyrotron. We would also like to acknowledge Volker Erckmann and his 140 GHz Gyrotron Team at the Max Planck Institute for Plasma Physics in Greifswald, Germany for providing recent long-pulse data on the 140 GHz gyrotron.

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