Recent Test Results on a 95 GHz, 2 MW Gyrotron*

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***Abstract*— A 95 GHz, multi-megawatt continuous-wave (CW) gyrotron oscillator is currently under development at CPI. During the initial experimental campaign peak output power levels up to 1 MW at 40A beam current were demonstrated at pulse lengths up to 5 ms. In addition, pulses up to 15 s in duration at 25 A beam current, the long-pulse limit of the CPI test stand, and 630 kW peak output power were achieved. Since the initial tests, modifications to the CPI test stand were made to allow for short-pulse operation up to 75 A. A second test campaign, aimed at demonstrating peak output power in excess of 1 MW, is now underway. Power levels up to 1.45 MW have been obtained thus far but efficiencies at higher beam currents appear to be limited by oscillations in the beam tunnel portion of the tube. Efforts to understand the cause of the oscillations are in progress.**

I. Introduction And Background

LONG-pulse and CW gyrotrons with output power levels of up to 1 MW are now routinely employed in present-day magnetic fusion installations for electron cyclotron heating and current-drive applications.[1] For ITER, a gyrotron employing a coaxial interaction cavity is being developed with the goal of providing an output power of 2 MW.[2] Recently, CPI began development of a 95 GHz gyrotron that is designed to generate CW output power levels in excess of 2 MW using a conventional gyrotron cavity. In addition to the high output power level, a second goal of this effort was to minimize system size and weight. With these basic goals, a prototype gyrotron was designed, fabricated and is currently being tested.

The 95 GHz gyrotron design is centered around an interaction cavity that is resonant in the $TE_{22,6,1}$ mode. This is the same cavity mode that is employed in 1 MW gyrotrons at a frequency of 110 GHz.[3] While the lower frequency mitigates some of the increased power density resulting from the higher output power levels, the peak wall loading of 1.8 kW/cm^2 is 50% higher than for the 110 GHz gyrotrons. The electron gun that produces the 90-kV, 75-A hollow electron beam for interaction with the $TE_{22,6,1}$ cavity mode has a single-anode configuration. Output power produced in the interaction cavity is transformed into a fundamental Gaussian beam using an internal converter that consists of a dimpled-wall launcher and three focusing and phase-correcting mirrors. The Gaussian beam exits the tube through an output window that consists of an edge-cooled, chemical-vapor-deposition (CVD) diamond disc that has a thickness of 2 mm and a clear aperture of 88 mm. The spent electron beam is dissipated in a 40.6-cm diameter collector. The collector is the portion of the tube where the greatest weight savings were realized. The collector operates at a depressed voltage of 61 kV to minimize the amount of power absorbed and improve overall device efficiency. A time-varying magnetic field is applied by modulating a magnet coil to sweep the beam axially along the collector surface to reduce the time-averaged power densities to manageable values. By employing dispersion-hardened copper instead of regular OFHC copper, the collector could be made to handle higher incident power densities while being more resistant to the cyclic fatigue effects from the axially-swept beam. In addition, the higher-strength alloy makes it possible to employ thinner collector walls that reduce weight and afford greater penetration of the modulated collector magnetic field because of lower eddy-current losses. The completed 95 GHz gyrotron weighed approximately 650 kG. For comparison, a 110 GHz, 1 MW gyrotron weighs about 1150 kG. A photograph of the gyrotron is shown in Fig. 1.

Fig. 1. Photograph of 95 GHz gyrotron.

II. Results

Initially, the test facility at CPI was limited to beam currents of 25 A CW and pulsed beam currents of 40 A. Tests on the gyrotron were carried out up to the test set limits in 2007. At 25 A, output power levels up to 630 kW were obtained for 15-

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s pulses and at 40 A, power levels of 1080 kW were measured during short-pulse (~5 ms) operation. In Fig. 2 we show a mode map where peak output power is plotted as a function of gun and main magnet coil current, during operation at a beam current of 40 A and a beam voltage of 90 kV, without collector depression.

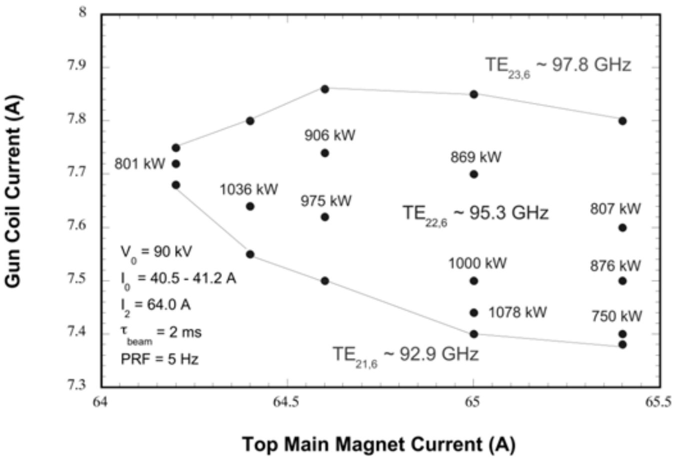

Fig. 2. 40 A mode map for 95 GHz gyrotron.

Since the completion of these initial tests, test-set modifications were implemented to enable operation at short-pulse beam currents up to the nominal value of 75 A. In the spring of 2008 short-pulse tests at beam currents up to 75 A were begun. An example of high-current operation is shown in a 60-A mode map in Fig. 3. As indicated in the figure, the maximum power at 60 A is about 1.28 MW. This data was taken with the nominal design collector depression voltage of 29 kV and collector-to-cathode voltage of 61 kV. This yields a total output efficiency of 35%. However, the interaction efficiency is only about 24%, which is significantly lower than the interaction efficiency of 30% at 40 A (see Fig. 2). The trend of lower interaction efficiency continued at higher current values as shown in Fig. 4 where we plot output power and total efficiency as a function of cathode-to-collector voltage for a constant accelerating voltage of 90 kV and a beam current of 70 A. The output power of 1.35 MW (and interaction efficiency of 21%) stays nearly constant over the full range of collector depression voltages indicating that depressing the collector does not affect interaction efficiency, only total efficiency. The maximum power observed during tests was 1.45 MW at a beam current of 75 A and the nominal accelerating voltage of 90 kV.

Though the cause of the efficiency decrease at higher beam currents is not yet fully understood, we believe that an oscillation in the beam tunnel region just prior to the interaction cavity is most likely a major contributing factor. Power absorbed in the beam tunnel and cavity region is measured calorimetrically during tests. At beam currents below 30 A, the amount of power lost in the cavity-beam tunnel region is about 2% of the total output power. This is in the line with expected losses in the interaction cavity. However, as beam current increases, the percentage of output power measured in the beam tunnel-cavity cooling circuit increases significantly to the point where more than 10% of the output power is measured in the beam tunnel circuit. We have also measured spurious frequencies in the 87-89 GHz range that begin appearing as the beam tunnel-cavity power begins to increase. We are in the process of making detailed analyses of the beam tunnel to determine the cause of the oscillations. Once tests have been completed the tube will be rebuilt to address the beam tunnel oscillations and any other improvements identified during the remaining tests.

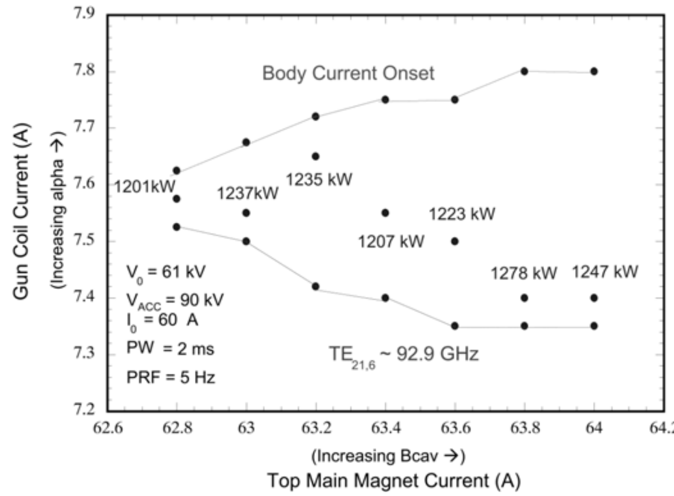

Fig. 3. 60 A mode map for 95 GHz gyrotron.

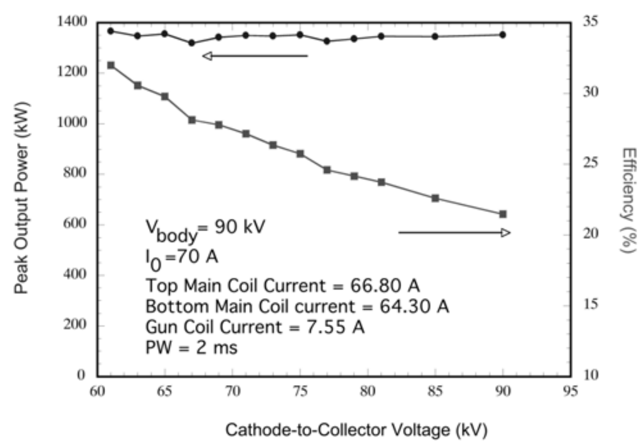

Fig. 4. Output power and efficiency vs. cathode-to-collector voltage for a beam current of 70 A.

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