DEVELOPMENT OF LONG-PULSE, MEGAWATT-CLASS GYROTRON OSCILLATORS AT 110 AND 140 GHZ

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Megawatt-class gyrotrons oscillators at 110 and 140 GHz are currently under development at CPI. An effort aimed at extending the capabilities of the previously demonstrated 110 GHz, 1 MW power level gyrotrons has resulted in the design and fabrication of a $TE_{22,6,1}$ mode gyrotron capable of producing 1.5 MW. Fabrication of the 1.5 MW 110 GHz, designed to operate at 96 kV and 40 A, is nearing completion and tests are scheduled to commence in 2004. In addition, a megawatt-class 140 GHz gyrotron was recently demonstrated at CPI. Peak output power levels up to 930 kW were achieved at 5-ms pulse lengths. At the 500 kW output power level, pulses up to 700 seconds in duration were demonstrated. The 140 GHz gyrotron has been shipped to the Wendelstein 7-X facility in Greifswald, Germany, where long-pulse testing up to 300 seconds will be carried out at the 930 kW power level in 2004.

1.5 MW 110 GHz Gyrotron

In many respects, the design of the 1.5 MW, 110 GHz gyrotron is similar to that of the 1 MW device previously developed and demonstrated by CPI [1]. Although the optics and high-voltage designs of the electron gun for the 1.5 MW 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. The interaction cavities of both the 1 and 1.5 MW gyrotrons are designed to operate in the $TE_{22,6,1}$ mode, but the cavity has been modified to optimize the efficiency for an output power level of 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 1.5 MW device consists of a rippled-wall launcher and four mirrors to convert the $TE_{22,6}$ mode produced in the cavity to a fundamental Gaussian mode at the output of the gyrotron. The CVD diamond output window for the 1.5 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 apertures on the previously demonstrated 84 GHz and 140 GHz tubes. 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 1.5 MW gyrotron, collector depression will be employed to reduce the amount of power that must be dissipated in the collector and also to increase the overall device efficiency. Initially, a single-stage depressed collector, with a configuration similar to the 84 GHz and 140 GHz gyrotrons [1], will be used. In a subsequent series of tests, a two-stage depressed collector, designed by Calabazas Creek Research [2], will be installed. A second departure from the 1 MW collector design involves the collector size and collector-coil geometry. The collector for the 1.5 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 1.5 MW design will use 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 1.5 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.

Fabrication of the 110 GHz, 1.5 MW gyrotron is nearing completion and the first tests are scheduled for 2004. A schematic diagram of the gyrotron is shown in Fig. 1 and a photograph of the nearly finished device is shown in Fig. 2.

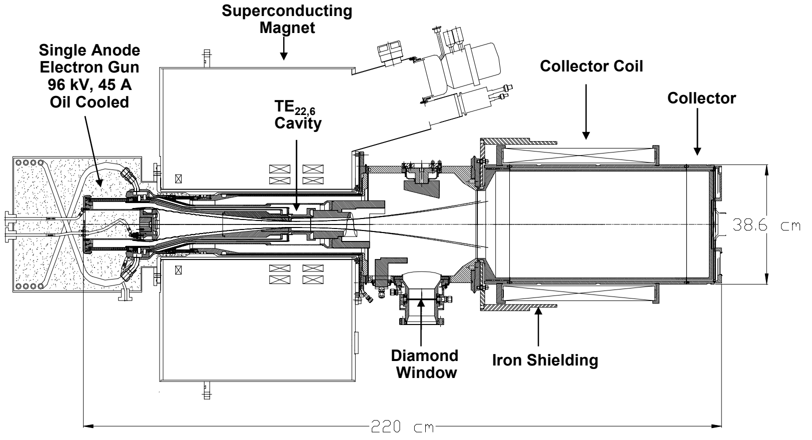

Figure 1. Schematic diagram of the 1.5 MW 110 GHz gyrotron.

Figure 2. Photograph of the 1.5 MW 110 GHz gyrotron.

1 MW 140 GHz Gyrotron

A 1 MW power level, long-pulse 140 GHz gyrotron oscillator was recently demonstrated at CPI. Key features of the gyrotron include a single-anode magnetron injection gun, which operates at 80 kV and 45 A in air; a $TE_{28,7,1}$ interaction cavity; an internal converter, consisting of a rippled-wall launcher and three mirrors which focus, phase correct, and steer the launched beam; an 88 mm diameter aperture edge-cooled CVD diamond output window; and a single-stage depressed collector for efficiency enhancement.

Testing of the 140 GHz gyrotron was carried out in the Spring of 2003. In short-pulse (< 5 ms) tests, peak power levels above 900 kW were achieved with efficiencies of 34%. Figure 3 shows a map of output power for varying cathode magnetic field, which results in a variation in the beam pitch factor, α, and interaction region magnetic field. 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 output power was measured to be 923 kW, which corresponds to 34% efficiency. As the magnetic field at the cathode was lowered and, thus, α was raised, the power slowly decreased. At sufficiently low values of cathode magnetic field, the onset of body current was observed.

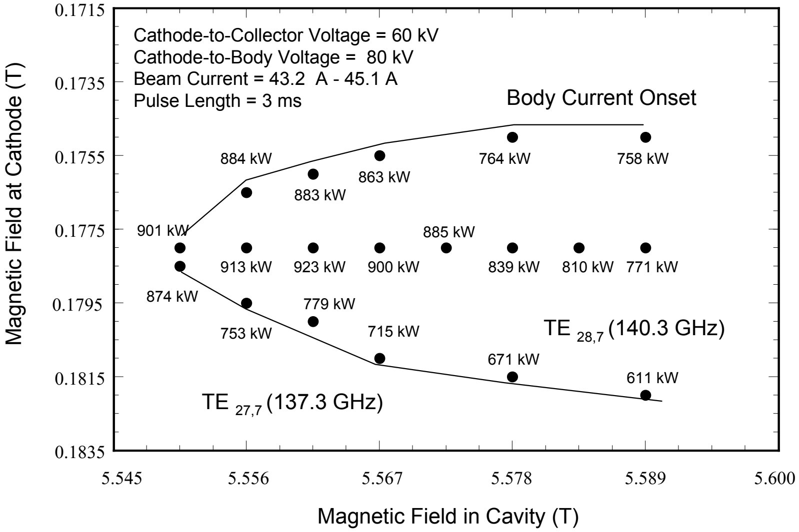

Figure 3. Measured output power for varying magnetic fields in the cathode and interaction cavity regions.

At lower interaction magnetic field values the $TE_{27,7,1}$ mode at 137.3 GHz was observed. Despite the lack of competition with the $TE_{25,8,1}$ mode, output power levels of 1 MW, the design value, were not achieved. As shown in the figure, mode competition from the $TE_{27,7,1}$ mode at 137.3 GHz prevented operation in the $TE_{28,7,1}$ mode at the design magnetic field, 5.52 T. Possible causes for the increased mode competition and lower than predicted output powers include non-ideal electron beam effects, such as higher than expected velocity spread or azimuthal asymmetries in the beam, or limitations of the large-signal design tool.

Before proceeding to high-duty and long-pulse operation, collector-power-density measurements were made to determine the distribution of the spent beam on the collector walls. The measurements were performed with an array of 192 temperature sensors attached to the outside wall of the collector. Measurements showed that at the 923 kW point, for 60 kV cathode-to-collector voltage and 45 A beam current, the maximum power density is approximately 700 W/cm^2. Measurements also showed that the spent electron beam was well spread in the axial direction and relatively uniform in the azimuthal direction. In additon, detailed power balance measurements were also performed to verify that the input beam power could be calorimetrically accounted for. The total diffraction losses in the gyrotron were measured to be 4.1% of the total generated RF power, which is in good agreement with the 5% diffraction losses predicted by theory. Also, the measured values of ohmic losses in the cavity and launcher, 2.5% and 1.8%, respectively, were close to the predicted values.

Following the verification of the power-density in the collector and the calorimetric power balance, long-pulse demonstrations began. Due to power supply limitations, pulse lengths longer than a few milliseconds could not be achieved at beam currents greater than 25 A. 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. Figure 4 shows a time-frequency trace for a 700-second pulse. Not visible in the figure is the 100-150 MHz frequency reduction in the first few hundred milliseconds of the pulse due to the initial cavity expansion. Over the rest of the pulse, the frequency decreases by less than 20 MHz. During the 700-second pulse, the currents measured on the two 25 l/s vacion pumps reached levels close to 1 μA in the first few seconds and did not rise appreciably after that time. The 700 second pulse ended without fault. In addition, ten 600-second pulses in a row were successfully made without fault.

Pulses longer than 700 seconds at the 500 kW output power level were not attempted due to heating in the collector depression ceramic caused by stray RF power not directed through the output window by the internal converter system. The temperature on the body-insulating ceramic, which was cooled with forced air, was measured as a function of pulse length. The measurements showed that the body-insulating ceramic temperature reached 105 degrees C after a 700 second pulse at the 500 kW power level. Though the ceramic temperature as a function of pulse length is beginning to level off at 700 seconds, use of improved air or oil-cooling of the ceramic should enable CW operation of the gyrotron at the 500 kW level for arbitrarily-long periods of time.

The 1 MW 140 GHz gyrotron has been shipped to the Wendelstein 7-X facility in Greifswald, Germany, where long-pulse demonstrations up to 300 seconds will be carried out at the 930 kW power level in the Summer of 2004.

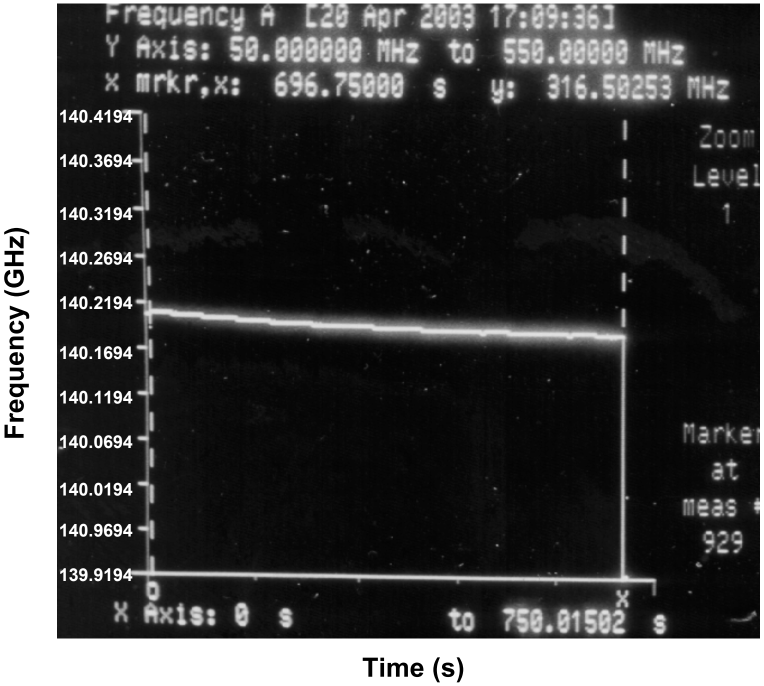

Figure 4. Time-frequency trace for a 700-second pulse at the 500 kW output power level.

References

[1] K. Felch et al., "Recent Tests on 500 kW and 1 MW, Multi-second-Pulsed Gyrotrons," Proceedings of the 12th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Heating, Aix-en-Provence (France) May 13-16, 2002, pp. 565-570.

[2] R.L. Ives et al., "Design of a Multistage Depressed Collector System for 1 MW CW Gyrotron," IEEE Transactions on Plasma Science, **27**, No.2, April 1999, pp. 503-511.