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Gyrotrons for magnetic fusion applications at 110 GHz and 170 GHz

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Abstract. Two megawatt-class gyrotrons at frequencies of 110 GHz and 170 GHz have recently been fabricated at CPI. The 110 GHz gyrotron is designed to produce 1.2 MW of output power for 10-second pulses, and will be used for electron cyclotron heating and current drive on the DIII-D tokamak at General Atomics. This gyrotron has completed factory testing and has been delivered to General Atomics for installation and additional testing. The 170 GHz gyrotron, though specified as a 500 kW CW system, has been designed with the goal of generating up to 1 MW CW. Oak Ridge National Laboratory will use this gyrotron in ITER ECH transmission line testing. This gyrotron has been fabricated and is awaiting factory testing, Design features of each gyrotron are described, and test data for the 110 GHz gyrotron are presented.

1 Design and testing of a 1.2 MW, 110 GHz, 10-second gyrotron

CPI's VGT-8115 gyrotron is specified to generate 1.2 MW of output power at 110 GHz, for pulse lengths up to 10 seconds. The gyrotron design is based on that of an earlier prototype [1], but incorporates several improvements, including a larger collector formed from a strengthened copper alloy, as well as a numerically-optimized dimpled-wall launcher and phase-correcting mirror system. The gyrotron operates in the magnetic field produced by a 43 kG superconducting magnet system (SCM) with three separately controllable axial coils (two for generating the desired field in the gyrotron cavity region, and one for adjusting the field at the cathode location) and two orthogonal sets of transverse field coils to ensure that the electron beam is centered in the cavity. The SCM cryostat maintains the necessary temperatures for the superconducting coils using a sealed refrigeration system that does not consume liquid cryogens. The gyrotron employs a single-anode magnetron injection gun to generate an annular electron beam. The electron beam interacts with the $TE_{22,6,1}$ mode of the cylindrical interaction cavity, and this mode is converted to a Gaussian output beam using the optimized launcher and mirror system. The Gaussian beam passes through an edge-cooled chemical vapor deposition (CVD) diamond disc window. The depressed collector dissipates the residual power in the electron beam by using a combination of iron shielding to expand the size of the annular beam and active sweeping with a large collector coil to vary the beam strike point and lower the time-averaged power-density. A schematic of the gyrotron layout is shown in Figure 1.

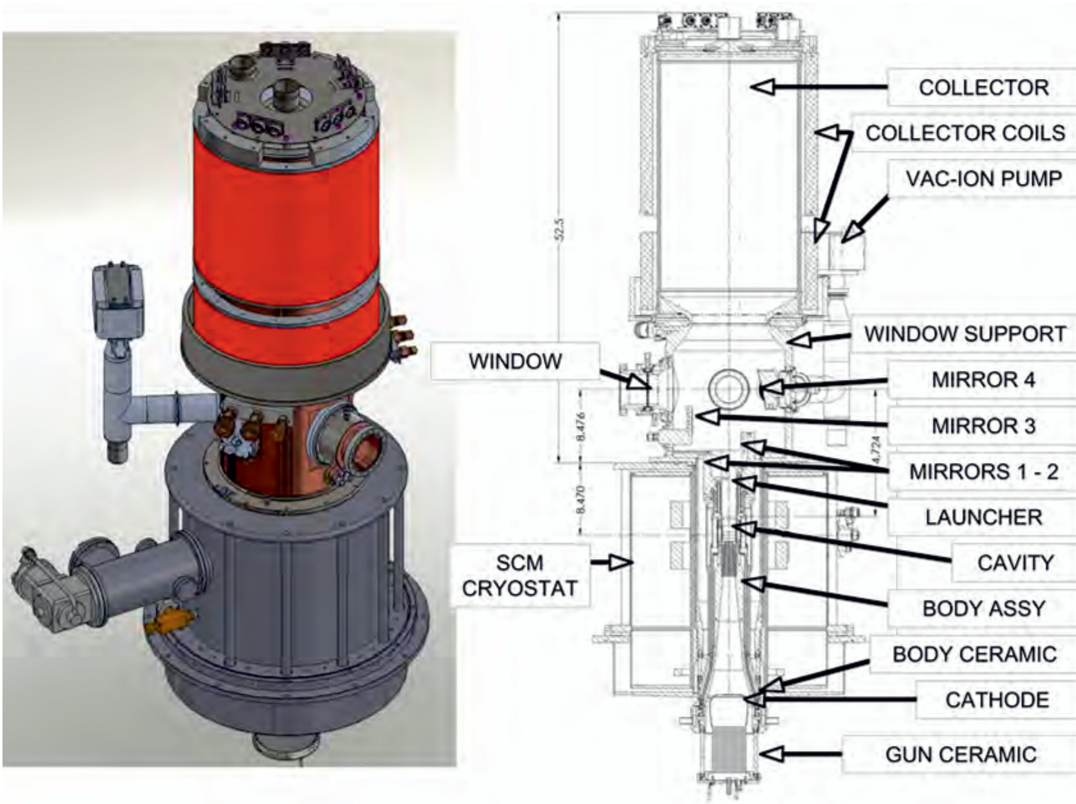

Figure 1. Schematic layout of CPI's VGT-8115 (110 GHz, 1.2 MW, 10 second) gyrotron.

The first gyrotron incorporating this updated design (VGT-8115 S/N 2) has completed factory testing at CPI, where it demonstrated 1.2 MW output power for short (5 ms) pulses, and 480 kW output power for 10-second pulses at the 25A CW current limit of CPI's test facility. Nominal operating conditions are listed in Table 1. Figure 2 shows output power and dissipated collector power vs. cathode-to collector voltage (for a fixed collector depression voltage). Figure 3 shows output power vs. beam current, with all other parameters held constant.

Table 1. Nominal Operating Conditions.

Parameter	Value
Cathode Voltage	-65 kV
Body Voltage	+29 kV
Collector Voltage	0 kV
Cavity Magnetic Field	43 kG
Interaction Mode	$TE_{22,6,1}$
Output Mode	Gaussian (TEM_{00})
Beam Current	45A
Output Power	1.2 MW
Efficiency	41%

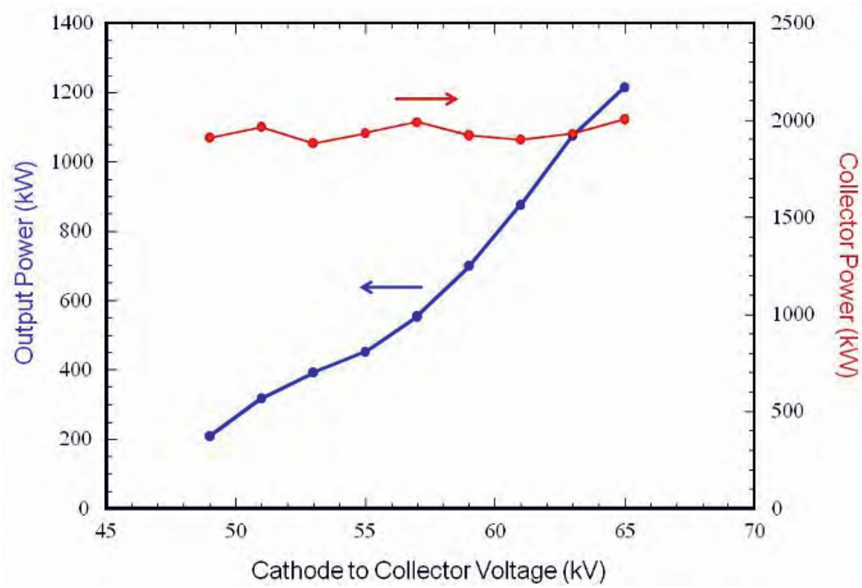

Figure 2. Calorimetrically measured RF output power, and spent beam power absorbed in the collector, as functions of the cathode-to-collector voltage, for the VGT-8115 S/N 2 gyrotron. Superconducting coil currents were $I_{main\text{-}upper}$=39.7 A, $I_{main\text{-}lower}$=43.0 A, $I_{gun\text{-}coil}$=0.37 A, and collector depression (i.e. collector-to-body voltage) was 29 kV. Cathode heater power was kept constant, so beam current varied with voltage. The beam current at 65 kV was 45 A.

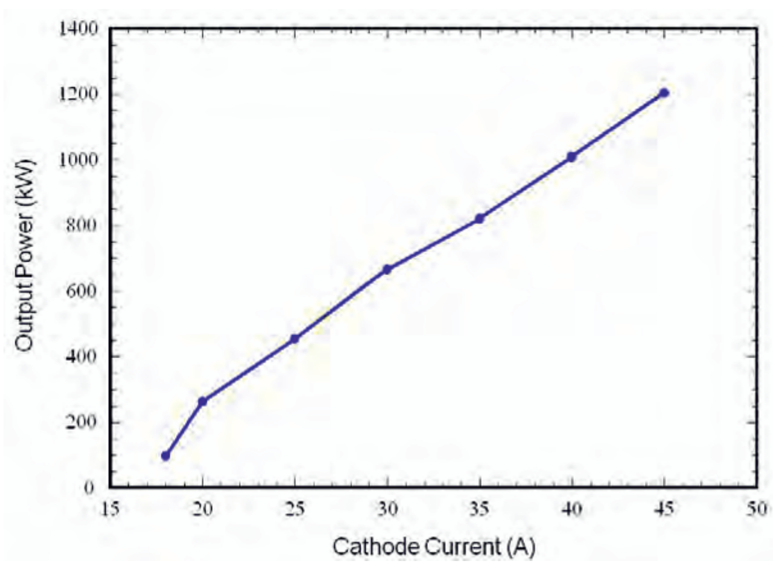

Figure 3. Calorimetrically measured RF output power as a function of beam current, for the VGT-8115 S/N2 gyrotron. Cathode-to-collector voltage was 65 kV, and collector-to-body voltage was 29 kV (for a total accelerating voltage of 94 kV).

After factory testing was completed, the gyrotron was delivered to General Atomics, where it will be tested to full-power and full-pulse length prior to use in electron cyclotron heating and current drive experiments on the DIII-D tokamak. A second identical gyrotron (VGT-8115 S/N3) is currently being fabricated.

2 Design and fabrication of a 500kW-1MW, 170 GHz, CW gyrotron

CPI's VGT-8170 gyrotron is officially specified to generate continuous output power of 500 kW at a frequency of 170 GHz. All gyrotron features and components have been optimized for operation at up to 1 MW of CW output power. The VGT-8170 gyrotron employs an electron gun with a modulating anode, to provide separate control of the beam radius, pitch factor, and voltage. 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 in order to reduce power dissipation in the collector and boost overall electrical efficiency. 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 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. As in the 110 GHz gyrotron, the 170 GHz gyrotron collector employs a strengthened copper alloy, as well as iron shielding to broaden the electron beam, and active magnetic sweeping to reduce time-averaged power densities to levels compatible with long life.

A schematic of the VGT-8170 gyrotron layout is shown in Figure 4. A key difference between the design approach employed for the 110 GHz gyrotron and that employed for the 170 GHz gyrotron is that the former uses a collector voltage depression ceramic located below the superconducting magnet, between the gyrotron body and the grounded assembly incorporating the window support structure and collector, while the latter uses a collector voltage depression

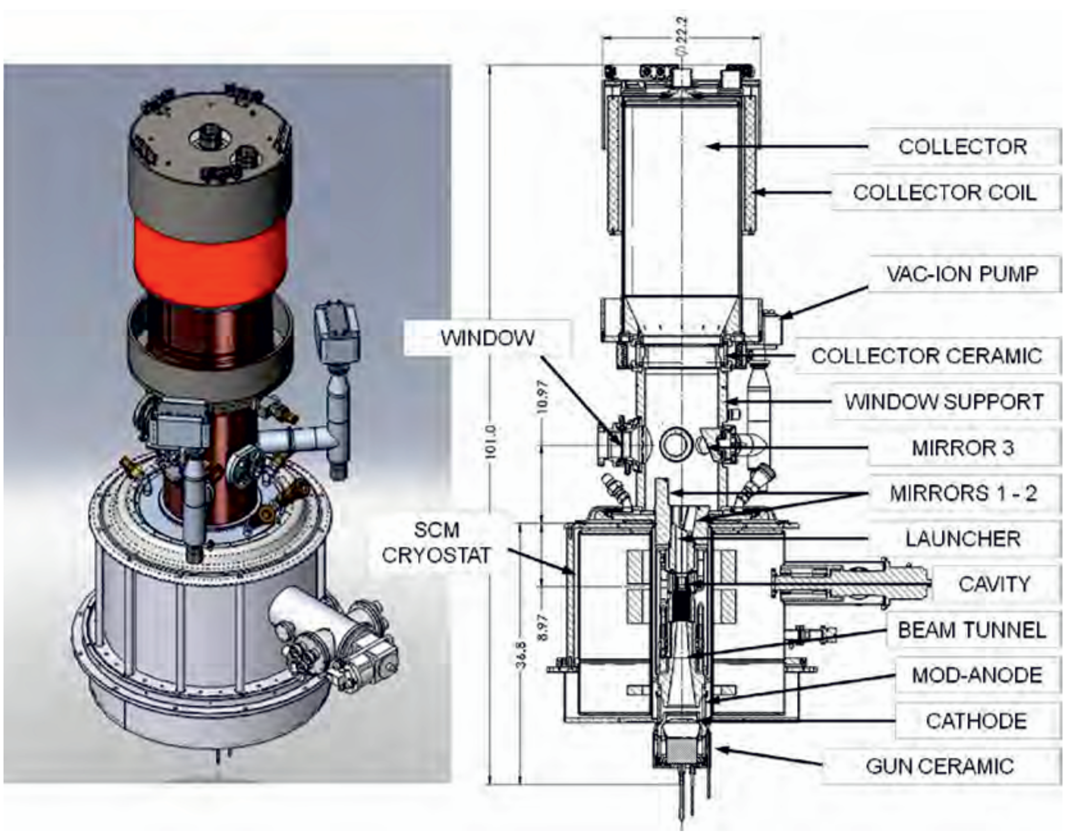

Figure 4. Schematic layout of CPI's VGT-8170 (170 GHz, 500 kW – 1 MW, CW) gyrotron.

ceramic located between the window support structure and the collector. While the latter approach maximizes the achievable collector depression voltage, and thus the overall efficiency, it does so at the cost of having the window at body potential, up to 30 kV above that of the grounded collector, necessitating the use of a DC break in the output transmission line system and additional safety precautions due to the presence of exposed high-voltage surfaces. The approach employed on the 110 GHz gyrotron results in somewhat lower achievable depression voltages, due to beam space charge depression effects in the window support region, but allows the window to be kept at ground, and restricts the exposed high voltage surfaces to the interior of the insulating oil bath located below the superconducting magnet.

The first VGT-8170 gyrotron (S/N 1) employing this design has been fabricated, and is scheduled to begin factory testing when the test facility becomes available. Once factory testing is completed, the gyrotron will be delivered to ORNL for use in a resonant ring being constructed for the purpose of testing ITER transmission line components [2].

References

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