Operation of a Quasioptical Gyrotron with Variable Mirror Separation

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Results from a quasioptical gyrotron experiment with a 20–28-cm mirror separation are presented showing operation from 95 to 130 GHz at powers up to 148 kW and output efficiencies up to 12%. The output coupling could be varied from 0.4% to 3% by changing the mirror separation and operating frequency. Efficiency optimization by variation of output coupling and by tapering the magnetic field has been demonstrated and regions of single-mode operation at powers up to 125 kW have been characterized.

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There is currently a need for megawatt average power sources of 100–300 GHz radiation for electron cyclotron heating of fusion plasmas. The leading candidate for such a source, the waveguide-cavity gyrotron,[1] has produced output powers of 765 kW and efficiencies of 30% at 148 GHz in a cw-relevant configuration.[2] However, this gyrotron configuration is limited at high frequencies by high Ohmic heating and problems with transverse-mode competition, due to the highly overmoded configuration, and with beam collection, since the beam must be collected along a section of the output waveguide. The quasioptical gyrotron (QOG), first proposed by Sprangle, Vomvoridis, and Manheimer,[3] features an open resonator formed by a pair of spherical mirrors instead of a waveguide cavity and has the potential for overcoming each of these limitations. The resonator mirrors can be well removed from the beam-wave interaction region, allowing a large volume for the interaction and low Ohmic heating densities at the mirrors. The beam direction is transverse to the cavity so that beam collection is separate from the output waveguide. The QOG operates in the lowest-order transverse (TEM_{00l}) Gaussian mode of the resonator, higher-order transverse modes being effectively suppressed by higher diffraction losses. Output coupling is via diffraction around the mirrors and can be controlled independently of other interaction parameters. The axial mode separation is small compared to the interaction bandwidth in cw-relevant configurations so that multimode effects are important. The theory of multimode operation was developed by Bondeson, Manheimer, and Ott.[4] The first QOG experiment was carried out by Hargreaves *et al.*[5] and used a resonator with a 4-cm mirror separation. Consistent with the relatively low axial mode density of this resonator, single-mode operation was observed at powers up to 80 kW at a frequency of 110 GHz and an efficiency of 11%.

This Letter presents results from a thorough and extensive experimental study of the first QOG to operate at powers over 100 kW using a cw-relevant resonator. The ability to vary the separation of the resonator mirrors from 20 to 28 cm allowed the resonator output coupling to be optimized with respect to the electron beam power. The QOG was tunable from 95 to 130 GHz and operated at powers up to 148 kW and output efficiencies up to 12%. The peak electronic efficiency is estimated to be 18% and is believed to be limited by the relatively low velocity pitch ratio, $\alpha = v_\perp / v_\parallel$, of the electron beam. The calculation of QOG efficiency is discussed in Ref. 4 in which theoretical efficiencies as high as 29% were reported for a configuration similar to the present experiment and $\alpha = 1.56$, which is considered achievable by state-of-the-art electron guns. The theoretical optimum single-mode efficiency of a conventional gyrotron with this α is higher, about 45%, due to the more uniform beam-wave coupling. The main effect responsible for the difference between the output and electronic efficiencies is Ohmic heating of the mirrors which can be a significant fraction of the total output at low output coupling. This effect becomes small at megawatt output power levels due to larger output coupling. Single-mode operation was observed at powers up to 125 kW. Conditions for single-mode operation in the highly overmoded system have been characterized. Efficiency optimization by variation of output coupling and by tapering the magnetic field have been demonstrated. These results point the way to the realization of megawatt level devices with output efficiencies of ~20%.

A schematic of the experiment is shown in Fig. 1. A 13-μsec pulse-length electron beam is generated by a Varian VUW-8010 temperature-limited MIG-type gun

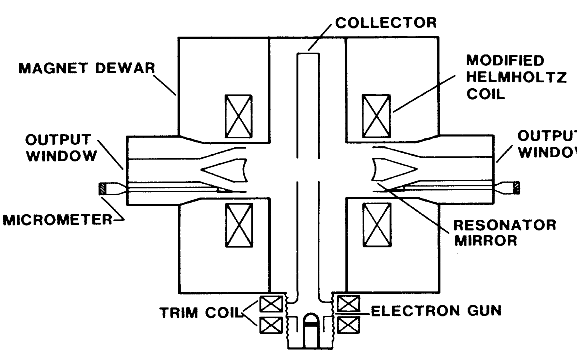

FIG. 1. Schematic of quasioptical gyrotron experiment.

which was operated at voltages up to 75 kV and currents up to 25 A. Magnetic fields of up to 50 kG in the interaction region and ~3 kG at the gun are provided by a pair of superconducting coils in a modified Helmholtz configuration, augmented by a pair of trim coils at the gun. The beam diameter in the resonator was 3.2 mm and the velocity pitch ratio was ~1. The magnet Dewar incorporates a 6-in. axial bore for the electron beam and a 4-in. cross-bore which contains the resonator mirrors and output waveguides. The presence of the cross-bore results in the magnetic field being 7% less than the axial maximum at the resonator. The gold-coated mirrors used in the experiment have a 38.7-cm radius of curvature and a diameter of 5 cm. The mirror separation is adjustable from 20 to 28 cm while under vacuum by means of six micrometers which also provide for mirror alignment and translation with respect to the electron beam. The radiation waist radius is $\omega_0 \approx 4.7\lambda$, where λ is the wavelength of the radiation. The resonator output coupling is via diffraction around the mirror edges and could be varied in the range 0.4%–3% depending on the operating frequency as well as the mirror separation. The diffraction losses increase with increased mirror separation. The microwave power is taken out equally around each mirror and is output through a pair of 0.013-cm-thick Mylar windows which are essentially transparent to all frequencies produced by the device. Frequency measurements were obtained using a heterodyne system in which the QOG output was beat against the signal from a 12–15 GHz tunable oscillator via a harmonic mixer. Power measurements were made with a laser calorimeter which is estimated to be 94% absorptive at 120 GHz based on reflectivity measurements.

Large-volume resonant cavities are inherently overmoded, and in this experiment the frequency separation between adjacent axial modes is ~0.5% which is much less than the interaction bandwidth (~5%). Thus, multimode effects, which are an issue for cw devices, could be investigated. On the other hand, the frequency separation between modes (~600 MHz) was easily resolvable by our frequency diagnostic system.

Extensive measurements, to be discussed in detail elsewhere, have been carried out for this configuration including threshold current studies, output power and efficiency measurements, oscillation frequency measurements, measurement of frequency tuning by varying the magnetic field and gun voltage, and studies of regions of single-mode operation. Threshold currents as low as a few tenths of an ampere were observed. At these currents the best fit between theory and experiment was obtained by assuming $\alpha = 1.5$. Based on previous experience with the electron gun at low currents, this is considered achievable. At higher currents it is estimated that the average α drops to ~1 with some additional dropoff expected for currents > 15 A. Figure 2 shows a comparison between measured and calculated threshold currents for a 25-cm mirror separation and a 57.6-kV gun voltage. The calculations are based on standard gyrotron theory modified for an open resonator and an annular electron beam.[4,6] The calculated resonator Q factor is 38 000 for 110 GHz radiation at this separation, including diffraction and Ohmic loading effects, and the total diffractive output coupling is 2.8%. The mirror positions and alignment were optimized to minimize the threshold current of the 109.8-GHz mode. Because of the thin beam geometry, and placement of the beam axis on a mode field maximum, alternate longitudinal modes are excited near threshold.

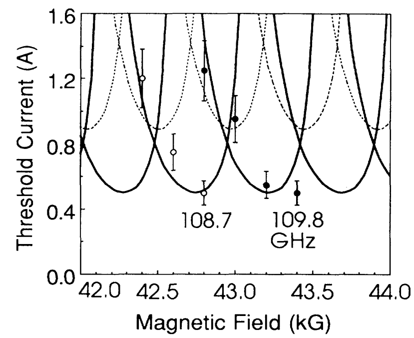

FIG. 2. Threshold currents for the axial modes of resonator with 25-cm mirror separation and a gun voltage of 57.6 kV. Data for the 109.8 ± 0.1- and 108.7 ± 0.1-GHz modes are shown by ● and ○ with error bars, respectively. Theoretical results assuming $\alpha = 1.5$ are indicated by the solid and dashed curves.

Output power measurements were carried out as a function of beam current, magnetic field, and mirror separation. The highest efficiency measurements were obtained at the minimum mirror separation of 20 cm. This minimizes the output coupling and so leads to the optimum saturated efficiency at the lowest current where beam quality should be highest. Mirror alignment and translation were optimized by minimizing the threshold current for a magnetic field of 50 kG and a beam voltage of 67.3 kV. A minimum threshold current of 0.25 A at a frequency of 125.8 GHz was obtained.

The output power was obtained by multiplying the calorimeter power measurement by 2, dividing by the pulse repetition rate and the pulse width, and correcting for the absorption efficiency of the calorimeter. The radiation pulse width was found to be equal (to a good approximation) to the beam-voltage flat-top pulse width of 13 μsec under most conditions and this pulse width was used in the peak power calculation. The output power symmetry through the two windows was checked and found to be equal within measurement accuracy. The calorimeter absorptivity was measured to be 94% at 120 GHz and to decrease with decreasing frequency to ~60% at 90 GHz. A conservative value of 95% was used in calculating the power for frequencies above 120 GHz.

The output power and efficiency as a function of beam current for a magnetic field of 50 kG and gun voltage in

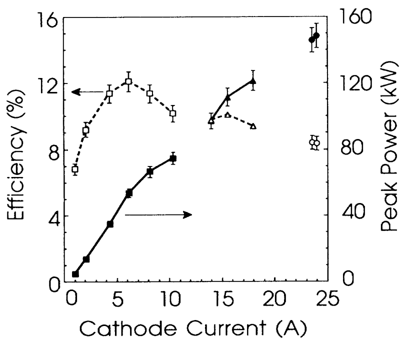

FIG. 3. Output power and efficiency operation with a 50-kG resonator magnetic field and gun voltages of 72–75 kV. The mirror separation for the data shown by the ■ and □ is 20 cm, and is 23 cm for the data shown by ●, ○, ▲, and △. The resonator magnetic field has a 2% negative taper for the data shown by ● and ○.

the range 72–75 kV are shown in Fig. 3. A peak efficiency of 12% was obtained at a current of 6 A. By calculating the power deposited on the mirrors, we estimate that this corresponds to an electronic efficiency of 18%. In obtaining these data no attempt was made to promote single-mode operation and, consequently, operation was generally multimoded with 4–6 modes being excited. The frequency of the strongest modes was ~125 GHz. The data indicated by the solid squares correspond to the minimum mirror separation of 20 cm and a gun voltage of 72 kV. The calculated diffractive output coupling at this separation is 0.4% for 125-GHz radiation. An outstanding feature of the QOG is the ability to increase output coupling (by moving the mirrors) nearly independently of other parameters. This allows the cavity rf fields to be maintained at the value for optimum efficiency while increasing electron beam and output power proportionally. In a conventional cavity gyrotron, the inability to vary the output coupling leads to overdriving of the cavity and a rapid decrease in efficiency beyond a certain current. The data indicated by the solid triangles and solid dots correspond to a mirror separation of 23 cm and 0.8% diffraction output coupling. The highest measured power, shown by the solid dots, was 148 kW and was obtained at a beam voltage and current of 75 kV and 24 A and a negative taper in the magnetic field of 2% across the interaction region. This current is estimated to be near the space-charge limit for this voltage and $\alpha = 1$. No evidence of oscillation in higher-order transverse modes was observed from the frequency measurements.

Although the fraction of the total power lost which is dissipated in Ohmic heating is high in the present configuration, the Ohmic heating density is relatively low. In the case of operation at 125 kW and a frequency of 120 GHz—demonstrated in this experiment with a 23-cm mirror separation and a 47-kG magnetic field—the average heating density (during the pulse) on the mirrors

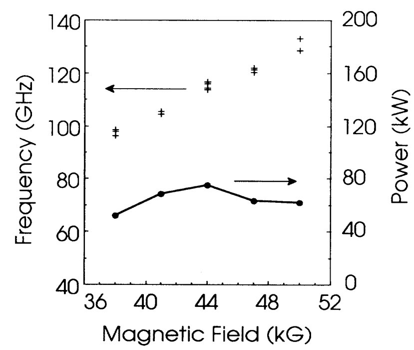

FIG. 4. Frequency tuning by magnetic field variation. The oscillation frequencies are shown by + and the output power is shown by ●.

was 0.6 kW/cm^2. The peak heating density of the approximately Gaussian mode was 3 kW/cm^2. These densities are within the average Ohmic heating limit of a few kW/cm^2 for cw applications. The spatial mode of the output radiation in the 2.25-in.-diam output waveguide was investigated using heat-sensitive paper. The burn patterns showed the power to be nearly azimuthally symmetric and peaked on axis. The radiation could be transported a distance of 2 m in the waveguide, which included a 90° H-plane miter bend, with negligible loss in power and little change in spatial pattern.

In the QOG the operating frequency is approximately Ω_c/γ, where Ω_c is the nonrelativistic cyclotron frequency and γ is the relativistic mass factor, so that the operating frequency can be tuned by varying the magnetic field or gun voltage. Figure 4 presents frequency and power measurements for magnetic fields from 38 to 50 kG with fixed gun voltage (67.3 kV) and current (12 A). The figure shows frequency variation from 95 to 130 GHz and <3 dB power variation. The QOG could have operated at still lower frequencies (at lower magnetic fields), but such frequencies were below the cutoff frequency of the waveguide used in the heterodyne frequency diagnostic. Frequency variation with voltage was also investigated and a 4% frequency increase was measured as the voltage was decreased from 72 to 43 kV. Howev-

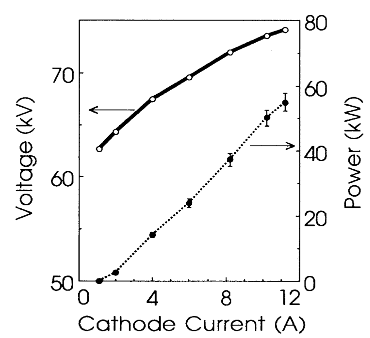

FIG. 5. Gun voltage and output power as a function of beam current for single-mode operation at 119 GHz.

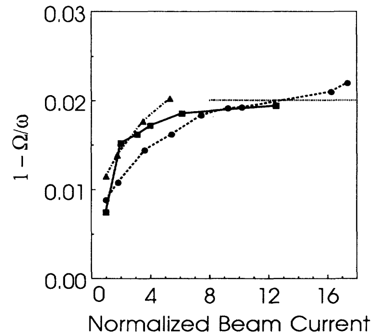

FIG. 6. Resonance frequency detuning of dominant mode plotted as a function of current normalized to the threshold current for a 47-kG magnetic field. The mirror separation is 20.5 cm for ●, 23 cm for ■, and 25.5 cm for ▲. Multimode simulation is based on Ref. 4 for ···.

er, power scales strongly with voltage and decreased from 70 to 25 kW.

Since the longitudinal mode density of the QOG resonator is high, it might be thought that the device is inherently multimoded, but this is not the case. At a fixed magnetic field and current near threshold, a single mode is driven. As the current is increased, the voltage can be varied to maintain single-mode operation. Figure 5 shows a region of single-mode operation (area denoted approximately by the line thickness) in V-I space. The maximum power of data in this figure is 55 kW. Other data were obtained showing single-mode operation at powers as high as 125 kW. As the current increases, the resonance frequency mismatch $\omega - \Omega_c/\gamma$ changes due to the nonlinear, multimode interaction. The multimode theory predicts that the frequency mismatch for the dominant mode is a function of the current normalized to the threshold current.[7] Figure 6 shows frequency mismatch versus normalized current for several different mirror separations and verifies this scaling. The theoretical detuning obtained from the multimode simulation code[4] is also shown. In plotting the experimental frequency mismatch, an approximate theory[8] was used to correct γ for space-charge depression of the beam in the open resonator.

The achievement of stable single-mode QOG operation relies on sideband suppression by the dominant mode, as in free-electron laser oscillators. A theory for predicting conditions for single-mode operation of free-electron lasers[9] has recently been extended to the QOG.[7] Consistent with our data, this theory indicates that sidebands can be suppressed for currents ~10–20 times the threshold current.

In summary, extensive results have been obtained for a cw-relevant QOG which demonstrate for the first time many of the advantages of this configuration at output powers up to 148 kW. A peak output efficiency of 12% was obtained. Single-mode operation was observed at powers up to 125 kW and the frequency was tunable from 95 to 130 GHz by varying the magnetic field. Efficiency optimization by variation of the output coupling and by tapering the magnetic field has been demonstrated.

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