Achievement of robust high-efficiency 1 MW oscillation in the hard-self-excitation region by a 170 GHz continuous-wave gyrotron

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Gyrotrons are a high-power source of coherent microwave radiation¹. Their oscillation mechanism is a cyclotron-resonance maser effect, in which a fraction of the rotational kinetic energy of a mildly relativistic magnetized electron beam is converted into electromagnetic energy. The most active area of gyrotron development is their potential use for heating magnetically confined fusion plasmas to the point of thermonuclear ignition. A major obstacle to this endeavour is that during high-power millimetre-wave operation^{2–9} competing modes and mode shifts seriously degrade a gyrotron's stability and efficiency^{10–13}. Here, we show that these problems can be overcome by active control of the electron-beam parameters during the oscillation. In doing so, we successfully demonstrate the robust steady-state operation of a 170 GHz gyrotron producing a continuous 1 MW output power with an unprecedented efficiency of over 55% in a hard-self-excitation region. Moreover, we find that an adjacent resonant mode previously expected to compete with and adversely affect the principal operating mode does not in fact jeopardize but rather helps this mode as a result of nonlinear effects. The result improves the outlook for using these devices for heating and instability control in future experimental fusion reactors, such as ITER^{14–19}.

A basic configuration of the high-power gyrotron oscillator used in the experiment⁷ is shown in Supplementary Information, Figs S1, S2. The nominal operation mode is TE_{31,8}, in a cylindrical open resonator, whose radius is 17.9 mm. An annular electron beam of 9.13 mm in radius is injected into the resonator along the axial magnetic field to excite TE_{31,8}. The oscillation millimetre-wave power P_{osci} is converted to a gaussian-like beam using a quasi-optical launcher^{20,21} attached to the resonator, and transmitted through an edge-cooled diamond window as P_{out} . Here, $P_{\text{out}} \sim 0.92P_{\text{osci}}$ due to the ohmic loss and the diffraction loss P_{loss} . The collector of the gyrotron is earthed. By applying a positive voltage $V_{\text{d.c.}}$ to the resonator section against the collector, the energy recovery of the spent electron beam is available to enhance the overall efficiency²².

After a demonstration of 1 h oscillation at $P_{\text{out}} = 0.6$ MW with fixed parameters, the operation parameters are actively controlled with a slow timescale to investigate the oscillation characteristics in the continuous-wave state. Figure 1a shows the dependence of

the output power on the magnetic field in the resonator, B_c . Here, $V_b \sim -72.5$ kV and $V_{\text{d.c.}} \sim 25.5$ kV. After the electron-beam I_b had stabilized at ~ 30 A completely, which takes ~ 1 min, the B_c scan started from 6.72 T. The frequency is ~ 170 GHz. The power increases as the B_c decreases, that is, the cyclotron resonance mismatch factor $\Delta' = (1 - (f_{ce}/\gamma f))$ increases. Here, f and f_{ce} are oscillation and non-relativistic cyclotron frequencies, respectively, and γ is a relativistic factor of the initial electrons. The maximum power of 0.8 MW is obtained at $B_c = 6.63$ T. The oscillation mode shifts from TE_{31,8} to TE_{30,8} (167 GHz) at $B_c = 6.625$ T. Then, the scan direction of B_c is reversed. The TE_{30,8} continues up to $B_c = 6.66$ T, and the oscillation returns to TE_{31,8}. A clear hysteresis effect^{23,24} on the generated RF power was observed, which is the first demonstration of the high power gyrotron by B_c scanning with continuous-wave operation. Dangerous reverse rotational modes TE_{–28,9} TE_{–27,9}, which cannot be transmitted to the output window, and other competing modes are not observed. Figure 1b is a corresponding numerical analysis, where self-consistent, single-mode equations are used²⁵. The B_c range in which two branches exist, $6.625 \text{ T} < B_c < 6.68 \text{ T}$, corresponds to the hard-self-excitation region. In the area enclosed between the solid and dashed lines (hatched region), TE_{31,8} has a positive growth rate and the power increases up to saturation at the solid line. TE_{31,8} ceases at $B_c \sim 6.625$ T because Δ' is too large to keep the oscillation, where the oscillation mode changes to TE_{30,8}. The numerically predicted radio-frequency (RF) power behaviour of the TE_{31,8} mode agrees very well with the experiment. The result indicates that maximum power is obtained in the hard-excitation region, and the power limit is not determined by the interruption from other modes but by its own oscillation limit. In addition, the result suggests that the voltage depression by the space charge of the electron beam is ~ 4.0 kV. A particle simulation predicts an average pitch factor α value of $\langle \alpha \rangle = 1.4$ ($\langle \alpha \rangle = \langle v_{\perp}/v_{\parallel} \rangle$, $v_{\perp}$ and $v_{\parallel}$ being respectively the perpendicular and parallel electron velocity with respect to the magnetic field) and a voltage depression of ~ 4.5 kV, which implies that the charge neutralization effect by ions was relatively small in this case. On the other hand, the single-mode simulation indicates that excitation of TE_{31,8} is possible at $B_c > 6.68$ T, whereas TE_{31,8} was re-excited at $B_c = 6.66$ T. There is a 0.02 T gap between them. In addition, the power of TE_{31,8} obtained for $|B_c|$ values

Figure 1 Output power versus magnetic field in resonator B_c . **a**, Experimental result at beam voltage $V_b \sim -72.5$ kV and beam current $I_b \sim 30$ A. The $TE_{31,8}$ mode is initially excited at $B_c = 6.72$ T, and B_c is scanned along the direction of the arrows. Just after the oscillation shift to the $TE_{30,8}$ mode, the B_c returned to higher field. Scan speed is 0.027 T min^{-1} . **b**, Single-mode simulation results at the parameter of the experiment for $TE_{31,8}$ and $TE_{30,8}$ modes. Arrows indicate the directions of mode shifts. The double-headed arrow shows the gap between the expected and measured magnetic fields of the mode shift. The hatched area shows the region where the $TE_{31,8}$ mode has a positive growth rate. $V_b = -68.5$ kV, $I_b = 30$ A, $\langle \alpha \rangle = 1.35$, and its deviation $\Delta \alpha / \alpha = 5\%$ are assumed.

during the increasing phase of magnetic field ($d|B_c|/dt > 0$) is higher than obtained for $|B_c|$ values during the decreasing phase. This discrepancy can be explained by the increase of the ions in the resonator in the $d|B_c|/dt > 0$ phase, which brings about the increase of the electron-beam energy. This acts, however, to enlarge the gap further from 0.02 to 0.03 T in the case of identical beam energy.

This gap is explained by a nonlinear excitation on a two-mode interaction¹⁰. Figure 2a is the simulation result of time behaviour of two modes²⁶, which are observed in the experiment, at $B_c = 6.67$ T. Here, as initial powers, 1 kW and 1 mW are set for $TE_{31,8}$ and $TE_{30,8}$ modes, respectively, to close up the feature. $TE_{30,8}$ grows to saturation in ~ 10 ns. $TE_{31,8}$ damps exponentially because the

Figure 2 Time behaviour of $TE_{31,8}$ and $TE_{30,8}$ powers calculated by multi-mode simulation code. $V_b = -68.5$ kV, $I_b = 30$ A. **a**, $t = 0-10$ ns. **b**, $t = 0-500$ ns.

oscillation condition is not fulfilled. However, when $TE_{30,8}$ exceeds ~ 10 kW, $TE_{31,8}$ begin to grow as a parasitic mode of the $TE_{30,8}$, because the electron phase bunching by $TE_{30,8}$ is also favourable for $TE_{31,8}$. As shown in Fig. 2b, $TE_{31,8}$ increases its power exponentially owing to $TE_{30,8}$. When the power exceeds the threshold (dashed line in Fig. 1b), $TE_{31,8}$ can grow by itself. $TE_{31,8}$ forces the electron phase bunching as favourable for $TE_{31,8}$ itself, and then begins to suppress $TE_{30,8}$. Finally, the system is dominated by $TE_{31,8}$, as observed in the experiment. These results imply that the adjacent $TE_{30,8}$ is not a competing mode for $TE_{31,8}$, but rather supports $TE_{31,8}$. As a result, the substantial soft-self-excitation region of the dominant mode is expanded.

The B_c scan was also performed at different values of α . The results are shown as power contours of objective $TE_{31,8}$ mode in Fig. 3. The vertical axis is the applied voltage between the anode and cathode terminals of the triode-type electron gun V_{ak} , which determines α . Generally, as V_{ak} is raised α increases, although it is not easy to identify the precise value of α . As a reference, the particle simulation indicates $\langle \alpha \rangle = 1.6$, 1.4 and 1.25 at $V_{ak} = 44$ kV, 42 kV (Fig. 1) and 40 kV, respectively. The solid line indicates the boundary between the $TE_{31,8}$ and $TE_{30,8}$ modes when B_c is scanned from the higher side, and the dashed line is that obtained for the inverse B_c scan. The region between the solid and dashed lines is the substantial hard-self-excitation region. Since the beam energy and current are stable, one can easily and precisely access the optimum without the mode shift and the electron trapping. The maximum power of 0.82 MW is obtained at the point denoted by

a star symbol, then the efficiencies are $\eta_{\text{RF}} (\equiv P_{\text{out}}/V_b I_b) = 36.2\%$ and $\eta_{\text{Total}} (\equiv (P_{\text{out}}/(V_b - V_{\text{d.c.}})I_b)) = 56\%$. The optimum point can be accessed through any pass in the $\text{TE}_{31,8}$ area. When B_c is decreased or V_{ak} increased, the leak current to the anode I_a appears at the hatched area in the figure. The cause of I_a is the electrons reflected by the depressed collector potential. If $V_{\text{d.c.}} = 21.5$ kV, I_a disappears because the minimum energy of the electron beam after the interaction is greater than 21.5 kV, and V_{ak} up to 44.0 kV is available. Here, the high-pitch-factor electron beam ($\alpha \sim 1.6$) is probably realized. Then, $P_{\text{out}} \sim 0.85$ MW and $\eta_{\text{RF}} = 39.1\%$ is obtained. The oscillation efficiency in the resonator is the highest value observed at 170 GHz gyrotrons; $\eta_{\text{osci}} (\equiv P_{\text{osci}}/V_b I_b)$ is 42.5%. These facts indicate that the perpendicular efficiency, which is defined as the conversion efficiency from the perpendicular energy of the electron to the RF energy, is close to $\sim 60\%$. Once the nominal operating mode is excited, the oscillation is robust and the operation parameters can be selected freely in the $\text{TE}_{31,8}$ region, including the hard-self-excitation region. However, when the parameters pass across the border and the adjacent $\text{TE}_{30,8}$ mode is excited, one should go back to the $\text{TE}_{31,8}$ region in the soft-self-excitation region to re-excite the nominal operating mode.

By increasing I_b to 38 A, the output power of 1.01 MW was obtained. Figure 4 shows an example of long-pulse oscillation. The total pulse duration is 1,100 s. After V_{ak} increases to 42 kV, B_c decreases slowly from 6.70 to 6.625 T. Then, the oscillation enters the hard-self-excitation region and the power increases to 1.0 MW. At the same time, the power deposition to the collector decreases with the same amount of power. For 800 s, the power exceeds 1.0 MW. No limit was seen for pulse extension. Here, $\eta_{\text{RF}} = 36.5\%$ and the overall efficiency with a 24.5 kV depressed collector is $\eta_{\text{Total}} = 55\%$. At deeper depressed collector, $V_{\text{CD}} = 26.5$ kV, $\eta_{\text{Total}} = 57\%$ is obtained at 1.0 MW, whereas a small amount of trapped electron $I_a \sim 5$ mA appears. The achieved results exceed the requirement on the gyrotron for ITER (International Thermonuclear Experimental Reactor), that is, 1 MW output power at 170 GHz, 50% efficiency, 500 s pulse duration (burning time of plasma), for a plasma heating and current drive to perform an experiment of self-ignition and plasma sustain^{14,15} (see Supplementary Information, Fig. S3). Furthermore, the achieved parameters in terms of RF power and global efficiency are consistent with the requirement for an electron cyclotron resonance heating–electron cyclotron current drive system to be installed on a future commercial reactor²⁷.

It should be noted that the high-efficiency state was difficult to attain without the active parameter control. In a conventional start-up scenario, the beam energy γ , that is, Δ' , and α are raised simultaneously, with a short timescale, which is usually less than 10 ms. However, important parameters such as I_b , α and f change significantly with a timescale of 0.1 s $\sim$ 1 min. Then, negative effects such as large electron trapping or mode shift occurred during the oscillation when the optimum operation parameters were initially fixed. To avoid these effects, the initial parameters were set such as to reach the maximum efficiency in the soft-self-excitation region, which brings about the efficiency decrease. For example, efficiencies of long-pulse gyrotrons were 36–43% with the depressed collector ($\sim 40\%$ in the case of 170 GHz)^{2,4–9}. In this paper it is proved that the accessibility to the maximum theoretical efficiency, in the hard-self-excitation region, is possible via the active parameter control, which allows a precise optimization of the relevant parameters such as $\langle \alpha \rangle$ and Δ' . Furthermore, by a combination of an active beam-position control that determines the coupling coefficient with each mode, more flexible operation will be available. The results give a possibility of high-efficiency oscillation at higher frequency²⁸, for example submillimetre to terahertz range, using further higher modes and higher-harmonic oscillation.

Figure 3 Power contour of the $\text{TE}_{31,8}$ mode with respect to B_c and the voltage between the control anode and cathode V_{ak} . $V_b \sim -72.5$ kV, $I_b = 30.0$ A. The hatched region is the region where the leakage current to the anode appeared. The star symbol is the point where the maximum power, 0.82 MW, was obtained.

Figure 4 Time behaviour of gyrotron parameters. Beam current I_b , output power P_{out} , magnetic field in the resonator B_c and collector temperature measured by the thermocouple. The output power of 1.0 MW is exceeded from 300 s. The frequency is 170.0 GHz at 1 MW output.

METHODS

POWER MEASUREMENT

The output power P_{out} was measured calorimetrically. In Supplementary Information, Fig. S4, the configuration of the gyrotron and transmission line of the output power is shown. The output power P_{out} couples with the HE_{11} mode of the corrugated waveguide using two mirrors in a matching optics unit, and the RF power is transmitted to a dummy load composed of pre- and main-dummy loads (1.25 MW waterload model 1250, Calabazas Creek

Research). All components are cooled by water; therefore, the deposition powers are identified from the temperature increases of the cooling water. The P_{out} of 1.01 MW is the summation of the dummy-load power (0.96 MW), transmission loss (~ 0.01 MW) and coupling loss dissipated in the matching optics unit (0.04 MW). As for Figs 1a and 2, P_{out} was measured from the temperature increase of the output window of the gyrotron made of a synthetic diamond disc using an infrared camera (TVS-8500, Nippon Avionics). The time constant of the window temperature is ~ 1.7 s, which is short enough compared with the scanning speed of B_c . The relationship between the window-temperature increase and P_{out} was obtained in advance.

ON B_c SCANNING

In Fig. 1a, B_c is scanned using a main magnet of the gyrotron. Generally, the change of B_c causes a shift of the beam radius r_b and the pitch factor α of the electron beam. However, in Fig. 1a, the scanning range is small (6.62 T–6.7 T). This gives small shifts of both r_b and α , that is, $\Delta r_b \sim 0.01$ mm and $\Delta \alpha \sim 0.01$, respectively, which have a small influence on the gyrotron oscillation. Therefore, no additional effort has been made to keep r_b and α constant in the experiment.

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Competing financial interests

The authors declare no competing financial interests.

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