EFFICIENCY ENHANCEMENT OF A 1.5-MW, 110-GHz GYROTRON WITH A SINGLE-STAGE DEPRESSED COLLECTOR

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We report new experimental results from a 1.5-MW, 110-GHz gyrotron with a single-stage depressed collector. The gyrotron was operated in the $TE_{22,6}$ mode with 3-μs pulse duration. An internal mode converter, which consists of a launcher and four mirrors, has been installed and tested. A highly Gaussian-like output beam was observed. A single-stage depressed collector has been operated for the study of efficiency enhancement using the same cavity V-2005 as was used in a previous experiment in the axial configuration, in which the output microwave beam propagated through a circular waveguide that also served as a collector. Output power of 1.5 MW, corresponding to 50% efficiency, was measured at 97 kV of beam voltage and 42 A of beam current at 25 kV of collector depression voltage. The results are compared between the axial configuration and the internal mode converter configuration.

KEYWORDS: *gyrotrons, high-power microwave sources, electron cyclotron heating*

I. INTRODUCTION

For many decades, gyrotrons have served as effective plasma heating sources for magnetically confined fusion experiments.[1–3] It has been proven in many experiments that electron cyclotron heating (ECH) in fusion tokamaks and stellarators has many advantages from a physics point of view.[4] It is well known that ECH waves can penetrate into a plasma and be absorbed at the local resonant area without issues of mode conversion. Also, electron cyclotron current drive can suppress neoclassical tearing modes in tokamaks so that stabilization of plasmas can be realized.[2,3,5] From a technological point of view, the recent development of gyrotrons makes ECH operation more effective and practical. Gyrotrons, unlike other microwave tubes, can produce high power (>1 MW) at high frequencies (>100 GHz) because of their intrinsic characteristics of operation. Since many gyrotrons are operated in high-order modes owing to the high-frequency operation, high output power can be stably generated with low ohmic loading of the cavity.[6] This is an advantageous feature of gyrotrons in plasma heating for fusion tokamaks.

High efficiency is very crucial for application in ECH systems, especially for ITER. In order to meet the ITER power-supply specification, gyrotrons have to be at least 50% efficient. Efficiency issues should also be resolved to further develop gyrotrons as powerful microwave sources. Most long-pulse gyrotrons have relatively poor efficiency (~30% without an energy recovery system) in the frequency range of 110 to 170 GHz at the power level of 1 MW.[7,8] Further efficiency enhancement can be acquired by means of depressed collectors. The spent beam energy is recirculated by depressing the collector potential instead of being dissipated at ground potential in the collector after the interaction in the cavity. Depressed collectors enable the gyrotron overall efficiency to be increased dramatically and also reduce the power loading at the collector surface, which could lead to collector failures by thermal overheating. Single-stage depressed collectors have been successfully demonstrated in gyrotrons experimentally.[7,9–11] However, recent work has shown that 50% overall efficiency at a power level of 1.5 MW at >100 GHz in long-pulse operation is still a major challenge even with a single-stage depressed collector.[7,8,12] The physics underlying the depressed collector scheme as well as the interaction phenomena in a cavity have to be understood in order to achieve 50% efficiency. In this paper, new results from the 1.5-MW, 110-GHz gyrotron with a single-stage depressed collector will be reported and discussed.

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II. EXPERIMENTAL SETUP

The nominal operating parameters of the gyrotron are shown in Table I. In the previous experiment the V-2005 cavity was tested in the axial configuration in which the microwave radiation propagates in the same direction as the spent electron beam, parallel to the gyrotron axis.[13] The V-2005 cavity parameters are summarized in Table II. The maximum output power was measured to be 1.67 MW, corresponding to 42% efficiency at 97 kV of beam voltage and 41 A of beam current (without a depressed collector). As the V-2005 cavity has excellent performance in terms of efficiency, further efficiency increase using depressed collector operation was the next goal for the research.

The internal mode converter (IMC) has been set up as shown in Fig. 1. The magnetron injection gun (MIG) and V-2005 cavity were the same in the new experiment as in the axial configuration.[13] The superconducting magnet produces a cavity magnetic field of 4.3 T. The tube features a four-mirror IMC and a single-stage depressed collector, which is isolated from the main tube by a ceramic separator. The IMC consists of a dimpled wall launcher, two focusing mirrors, and two phase-correcting mirrors, which convert the $TE_{22,6}$ cavity mode into a Gaussian-like output beam. A simple 12.7-cm-diam cylindrical geometry was used for the collector, which was designed properly to prevent high-voltage breakdown. Since the gyrotron was operated in short pulses, the average power loading on the collector in the experiment is small, which allows the collector size to be small. The output Gaussian-like beam propagates to the fused silica window, which has a 10.8-cm-diam aperture. The frequencies were measured using a heterodyne receiver. The power was measured using a 20-cm-diam dry calorimeter of Scientech Inc., Model 36-0801 (serial number 5000). The calorimeter consists of an aluminum plate covered with a layer of microwave-absorbing paint (3M Nextel paint). This plate is attached to a heat sink by an array of thermoelectric elements that monitor the temperature rise of the plate and also serve as a thermal conduction path to the heat sink.

TABLE I

Nominal Design Parameters for the Gyrotron

Frequency	110 GHz
Microwave power	1.5 MW
Beam voltage	96 kV
Beam current	40 A
Beam alpha ($\alpha = v_\perp / v_\parallel$)	1.4
Operating mode	$TE_{22,6}$
Pulse length	3 μs
Cavity magnetic field	4.3 T

TABLE II

V-2005 Cavity Design Parameters

Mode purity	99.78%
Frequency	110.07 GHz
Q factor (cold cavity)	837
Peak ohmic power (at 1.5 MW)	0.8 kW/cm^2
Normalized length (μ)	16.1
Power	1.62 MW

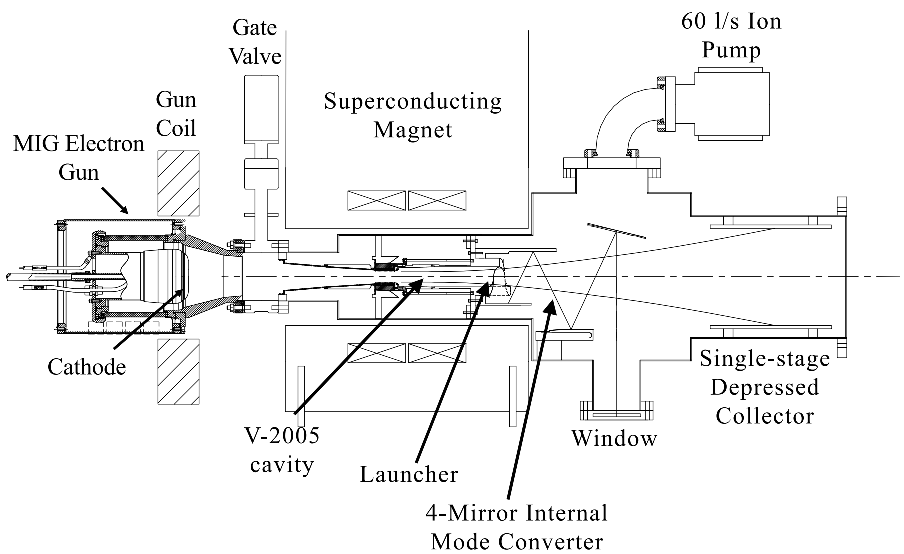

Fig. 1. The 1.5-MW, 110-GHz gyrotron schematic.

III. EXPERIMENTAL RESULTS

III.A. Internal Mode Converter Configuration

The output microwave beam was measured using a two-dimensional scan of a diode detector attached to a remotely controllable WR 10 attenuator. Figure 2 shows the output beam measurement result. The horizontal axis represents the axis parallel to the gyrotron, and the vertical axis represents the perpendicular direction to the gyrotron axis at the fixed microwave output beam axis (it was measured at 73.6 cm away from the window). The center of the graph is the beam center. The beam waist radius was determined to be 1.5 cm at the window, which is in good agreement with the design value. The beam was measured at several planes from the window and showed a highly Gaussian-like beam as shown in Fig. 2, although no effort has been made to take the phase measurement.

The V-2005 cavity performance was previously investigated in the axial configuration, and the results were analyzed to understand mode competition.[13] From the comparison between the axial configuration and IMC configuration, the IMC performance can be understood. Figure 3 shows the power measurement comparison of the IMC configuration to the axial configuration as a function of main magnetic field. The maximum power in the IMC configuration was 1.5 MW, corresponding to 37% of overall efficiency at 4.37 T of main magnetic field at 96.6 kV of beam voltage and 42 A of current. Output power of 1.67 MW corresponding to 42% of overall efficiency, was obtained in the axial configuration at the same operating parameters. From the comparison of the maximum power of the two configurations, 10% less power was measured in the IMC configuration. This power reduction can be attributed to several possible differences between the experiments, including losses in the internal converter and differences in the mode excitation physics for the two configurations. The possible explanations are discussed in Sec. IV.

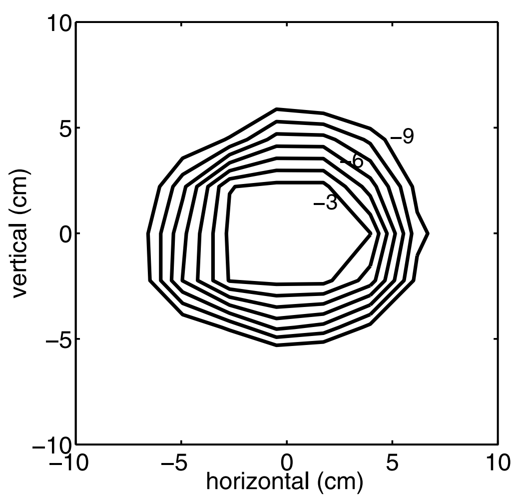

Fig. 2. Plot of the measured power of the Gaussian-like output beam at 73.6 cm from the window location along the output beam axis. The contours represent the intensity of the beam in dB between 3 and 9 dB down from the peak. Horizontal: parallel to the gyrotron axis; vertical: perpendicular to the gyrotron axis.

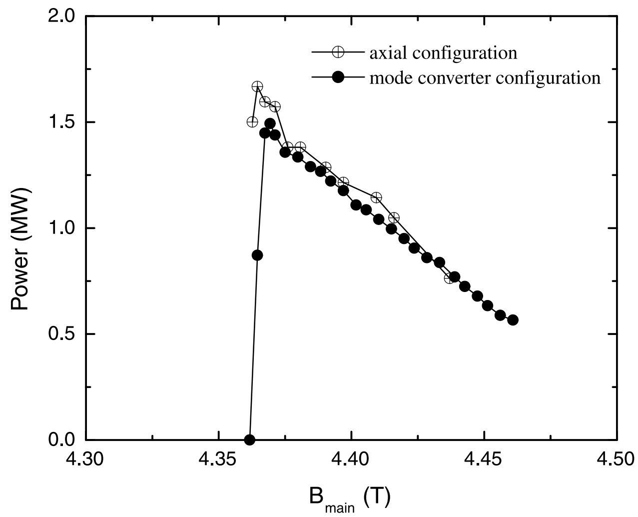

Fig. 3. Power measurement as a function of main magnetic field at 96.6 kV of beam voltage and 42 A of beam current. Open circles represent the axial configuration results, and solid circles represent the IMC configuration.

Figure 4 shows the mode map measurement, which represents possible modes excited in the cavity as the main magnetic field and gun magnetic field are changed. The $TE_{22,6}$ mode has a wide stable oscillation region as clearly seen in Fig. 4. A beam reflection region appears when the beam is overcompressed. When the beam is overexpanded, the beam starts to intercept with the cavity wall, which is marked as "Beam interception" in Fig. 4. A small region of the counterrotating $TE_{19,7}$ mode is excited because of the reflection of power at the launcher. In the experiment, the rotation of the $TE_{19,7}$ mode has been checked by changing the polarity of the magnetic field. The $TE_{19,7}$ mode was very unstable and produced low power when it was counterrotating mode in the experiment.

III.B. Single-Stage Depressed Collector Experimental Results

The schematic for the single-stage depressed collector is shown in Fig. 5. All components such as the beam tunnel, cavity, and the IMC are denoted as "cavity" in the schematic. The collector potential is depressed with respect to the body. High-power carbon resistors were used

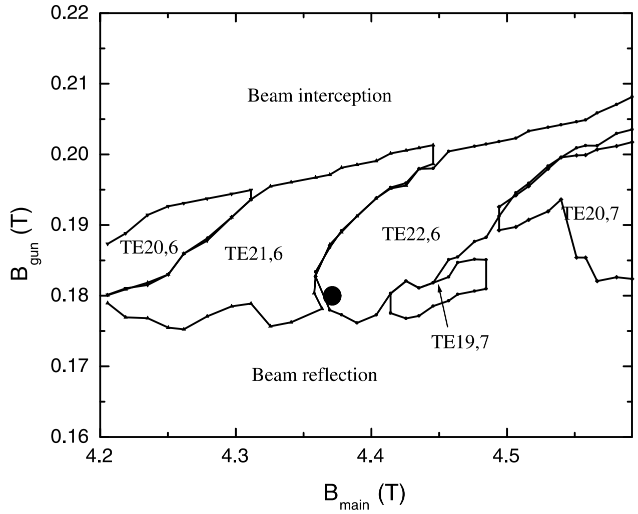

Fig. 4. Mode map plot in the IMC configuration measured at 96.6 kV of beam voltage and 42 A of current. The circle indicates the maximum power point.

for varying the collector voltages. The overall gyrotron efficiency η_t is now obtained from the following equation:

$$\eta_t = \frac{P_{output}}{(V_b I_b - V_{dep} I_{coll})} = \frac{\varepsilon_{out}\,\eta_{el}}{(1-\eta_{coll}(1-\eta_{el}))} \quad ,(1)$$

where

P_{output} = output microwave beam power

V_b = beam input voltage

I_b = beam current

V_{dep} = collector depression voltage

I_{coll} = current at the collector.

The radio-frequency (RF) losses inside the tube are described by the mode conversion efficiency ε_{out} $(= P_{output}/P_{\mathrm{RF}})$ where P_{RF} is the generated RF power and P_{output} is the RF output power after the launcher and mirrors. The electronic efficiency is represented by η_{el} $(= P_{\mathrm{RF}}/V_b I_b)$.

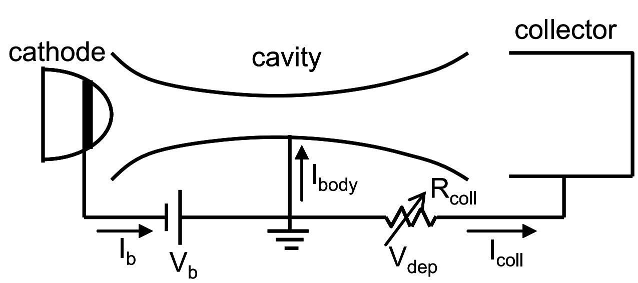

Fig. 5. A circuit schematic for the single-stage depressed collector.

The collector efficiency η_{coll} is defined as

$$\eta_{coll} = \frac{V_{dep} I_{coll}}{(V_b I_b - P_{\mathrm{RF}})} \quad . \tag{2}$$

Figure 6 shows a power and efficiency plot as a function of collector voltage. The power was maintained at 1.5 MW up to 25 kV of collector voltage. The body current starts to appear above 25 kV of collector voltage, and the power starts to drop. The gyrotron was operated stably up to 46 kV as shown in Fig. 6. However, the body current at 46 kV was not acceptable for long-pulse operation. It is interesting that the efficiency still rises up to 55% at 40 kV of collector voltage, though the large body current would prevent long-pulse operation under these conditions. Some electrons are reflected back to the cavity at more than 25 kV of collector voltage, which lowers the output power and leads to large values of the body current. Stable operation with no body current was obtained at 1.5 MW of output power at 25 kV of collector voltage, which corresponds to 50% of gyrotron efficiency and a collector efficiency of 44% from Eq. (2).

Figure 7 shows a plot of the threshold collector depression voltage above which the body current starts to appear, as the beam current is varied at a fixed beam voltage of 96.6 kV. The power (efficiency) values are 0.82 MW (49.3%), 1.1 MW (51%), and 1.5 MW (50%) at 30, 35, and 42 A of beam current, respectively. Alpha (velocity ratio $v_\perp/v_\parallel$) values have been measured to be around 1.3 by the capacitive probe situated before the entrance of the cavity with an accuracy of ±15% at each current.[14] At each point, the magnetic field was optimized to have a maximum efficiency. Circles and squares represent experimental measurements and simulation

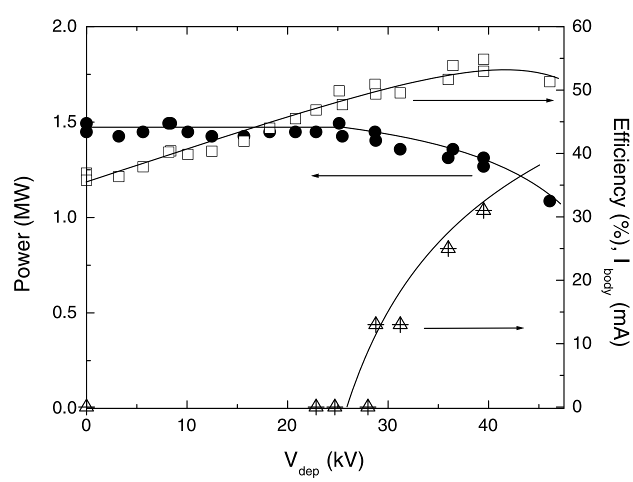

Fig. 6. Power, efficiency, and body current measurements as a function of depression voltage of the collector. Solid circles: output power; open squares: an efficiency plot; and open triangles: a body current plot.

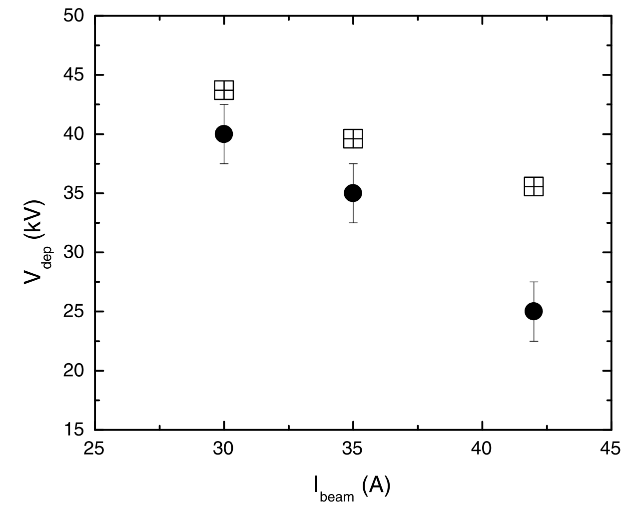

Fig. 7. A threshold collector depression voltage as a function of beam current at 96.6 kV of beam voltage. Circles with error bars represent experimental measurements, and crossed-squares represent the simulation results.

results, respectively. As the current decreases, the output power is lowered, which leads to higher minimum energy of the spent beam.[9] The MAGY code, a multimode and time-dependent gyrotron cavity simulator that was developed by the University of Maryland and the U.S. Naval Research Laboratory, has been used for simulating the spent beam energy.[15] Voltage depression in the cavity due to the space charge effect and velocity spread are included in the simulation. Figure 8 shows the beam distribution of energy at 42 A of beam current. In order to have the same output power of 1.5 MW as in the experiment, 7% of velocity spread and an alpha value of 1.3 were introduced into the simulation. A minimum energy of the spent beam of 35.6 kV was determined from the simulation.

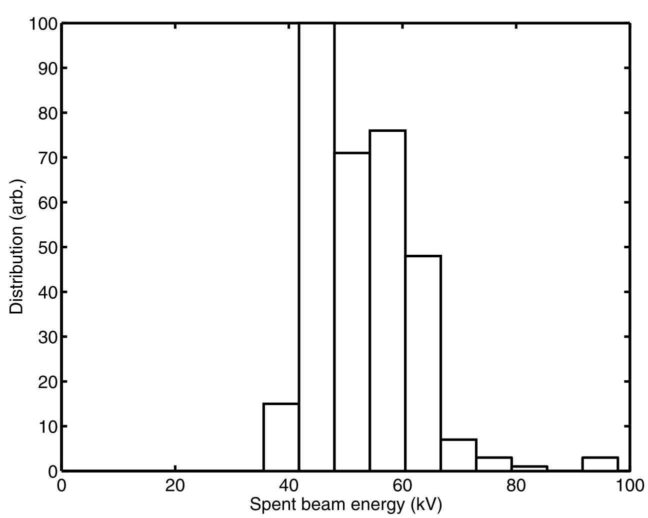

Fig. 8. Distribution of the spent energy of the electron beam at 42 A of beam current and 1.5 MW of output power. The number of electron beamlets used in the calculation was 81.

IV. DISCUSSION AND CONCLUSIONS

A 1.5-MW, 110-GHz gyrotron experiment with a single-stage depressed collector has been successfully carried out. A wide zone of stable oscillation of the $TE_{22,6}$ mode was obtained in the mode map. A single-stage depressed collector has been applied for this experiment. Very stable operation at a power level of 1.5 MW of output power, which corresponds to 50% gyrotron overall efficiency, was obtained experimentally at 25 kV of collector depression voltage without the appearance of body current. The depressed collector efficiency at 50% of gyrotron overall efficiency was 44%. The gyrotron has been previously tested in the axial configuration, yielding 1.67 MW of power corresponding to 42% efficiency without a depressed collector.[13] The IMC was employed in the present gyrotron while the same cavity, MIG, and SC magnet were used so that the comparison between the axial configuration and the IMC configuration is direct, reproducible, and reliable. The maximum power with the IMC was 1.5 MW at 96.6 kV of beam voltage and 42 A of beam current. From the comparison between the axial configuration, 10% of power loss was obtained. If there are no physics differences between the axial configuration and IMC configuration, the 10% reduction of power would be completely attributed to the IMC loss. The estimated loss due to the mode converter, which is an old design, is in the range of 6 to 9% using a recently developed mode launcher code.[16,17] However, some physics differences may be present in the experimental results. The maximum output power is obtained at slightly different values of the magnetic field at the gun and at the cavity for the axial and IMC configurations. This would indicate small differences in the beam alpha values and the mode excitation zones for the two configurations. These differences may also account for some of the reduced power in the IMC configuration.

From the power reduction in the IMC configuration compared to the axial configuration, it is clear that it is still possible to increase the gyrotron overall efficiency to much more than 50% if the IMC loss can be improved by a better design of the launcher and mirrors. Furthermore, increasing the depressed collector efficiency to more than 60% will bring up the gyrotron overall efficiency to 60%. A better understanding of the single-stage depressed collector experiment will help to design more efficient collectors. A two-stage depressed collector should be a very promising candidate for increasing the depressed collector efficiency.[18–20]

From the achieved results it seems very promising to have an efficiency >50% for a megawatt class of gyrotron, which meets the ITER specification.

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