Experimental results for a 1.5 MW, 110 GHz gyrotron oscillator with reduced mode competition

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A new result from a 110 GHz gyrotron at MIT is reported with an output power of 1.67 MW and an efficiency of 42% when operated at 97 kV and 41 A for 3 µs pulses in the TE_{22,6} mode. These results are a major improvement over results obtained with an earlier cavity design, which produced 1.43 MW of power at 37% efficiency. These new results were obtained using a cavity with a reduced output taper angle and a lower ohmic loss when compared with the earlier cavity. The improved operation is shown experimentally to be the result of reduced mode competition from the nearby TE_{19,7} mode. The reduced mode competition agrees well with an analysis of the startup scenario based on starting current simulations. The present results should prove useful in planning long pulse and CW versions of the 110 GHz gyrotron. © 2006 American Institute of Physics. [DOI: 10.1063/1.2171522]

I. INTRODUCTION

Gyrotrons have emerged as the most promising high power, high efficiency millimeter wave sources suitable for electron cyclotron heating (ECH) and electron cyclotron current drive (ECCD) in magnetically confined burning plasma experiments. Gyrotrons operate in very high order modes and can generate over one megawatt of CW power at frequencies up to 170 GHz. Recently, a Communication and Power Industries (CPI) 140 GHz gyrotron operated continuously with 800 kW of output power for more than 30 min.2 Research and development is underway on gyrotrons capable of producing over 1 MW of continuous wave power at 110, 140, and 170 GHz.3-8 To meet the requirements of a large ECH system9,10 as required in ITER, the overall efficiency of gyrotrons needs to exceed 50%. With the successful achievement of over 1 MW of output power in long pulses at up to 170 GHz, considerable effort is being made to improve the efficiency of gyrotrons to greater than 50%. The use of a depressed collector has enabled the recovery of about 2/3 of the energy from the spent electron beam and thus the reduction in the overall recirculating power in the gyrotron.11 This has enabled the reduction in size of the collector and overall improvement in the efficiency of the gyrotron. Improvements in the design of the internal mode converter and the matching optics unit (MOU) used to convert the high-order gyrotron operating mode into a free-space Gaussian beam are also being studied.

We present results from a 110 GHz, 1.5 MW power level gyrotron operating with a 3 µs pulse width in the TE_{22,6} mode. The TE_{22,6} mode has been successfully used in 1 MW industrial tubes12 and in our previous studies at the 1.5 MW power level.1 Operation at such a pulse width allows us to investigate various physics and microwave engineering issues of the design over a wider parameter space than is possible in a cw tube built by industry. The present study focuses on increasing the electronic efficiency of the gyrotron interaction by improving the cavity design. In previous research, we have reported the generation of 1.43 MW of power with 37% efficiency. The cavity used in those studies was also used in the industrial gyrotron and is designated the “V-2003” cavity. A new cavity, designated “V-2005,” was designed to have lower ohmic losses than the V-2003 cavity by reducing the output taper angle. Results for the cavity (V-2005) are reported here and they include an increase in efficiency to 42%. The reasons for the increase in efficiency of the low ohmic loss cavity go beyond the reduction of ohmic losses. It has been found experimentally that the new design is less susceptible to mode competition and thus allows access to the high efficiency operating regime. Theoretical modeling using a starting current simulation strongly supports the experimental results.

The paper is organized as follows. In Sec. II we present the results of our theoretical study of gyrotron efficiency variation as a function of the basic parameters of the cavity and present the design of the V-2005 cavity. The experimental setup is described in Sec. III and the experimental results are presented in Sec. IV. Theoretical modeling of the startup scenario of the V-2003 and V-2005 cavities and their comparison to experiment are detailed in Sec. V, followed by conclusions in Sec. VI.

II. CAVITY DESIGN STUDY

As the operating power approaches the MW level, the ohmic loss of the cavity wall and its dissipation become serious issues. The mean value of Ohmic loss density can be expressed by Eq. (1),13

$$P_{\text{ohm}} = \frac{Q_D}{Q_{\text{ohm}}} \frac{P_{\text{out}}}{2\pi RL} \approx \frac{P_{\text{out}}}{\lambda^2 R^2 (1 - m^2/n_{m,p}^2)} L \delta_{sk},$$

where $Q_D$ and $Q_{\text{ohm}}$ are, respectively, the diffractive and the ohmic quality factors, $P_{\text{out}}$ is the power exiting the cavity, $L$ is the cavity length, $\lambda$ is the wavelength, $R$ is the cavity radius, $m$ is the azimuthal index of the mode, $n_{m,p}$ is the...
eigenvalue of the $p$th root of $J_m'(\nu_m,p)=0$, and $\delta_{sk}$ is the skin depth, which is defined as

$$\delta_{sk} = \frac{1}{2\pi} \sqrt{\frac{\lambda c}{\sigma}}$$

where $\sigma$ is the conductivity of copper. From Eq. (1), it is evident that in order to limit the ohmic loss on the cavity wall to an acceptable value, it is advantageous to decrease the diffractive $Q$ factor. To systematically study the optimization of the cavity, we have chosen three basic parameters of the cavity, namely the input taper angle, the output taper angle, and the straight section length. The cavity consists of a straight section with a downtaper toward the gun and an uptaper toward the collector.

Based on the successful study of the previous cavity, V-2003, the new cavity was optimized using the multimode, self-consistent and time-dependent simulation code, MAGY, which was developed by the University of Maryland and NRL. The simulations were performed considering a triplet of modes around the operating mode $TE_{21,6}, TE_{22,6}, TE_{23,6}$. The design parameters for the gyrotron are listed in Table I. For a given value of the length of the straight section, the efficiency and ohmic loss can be calculated and plotted as a function of the input and output taper angles. The best results were obtained for a straight section length of 1.8 cm, the same as the length of the V-2003 cavity, and only results for that length are presented in this paper. The simulation results from MAGY are shown in Fig. 1. The variation in efficiency with input and output taper angles is shown in Fig. 1(a). In Fig. 1(b), we notice that the peak ohmic loading diminishes as the uptaper angle is reduced while maintaining the same output power and efficiency.

The points for the final designs of the V-2003 and V-2005 cavities are marked as a star and cross, respectively, in Fig. 1. The final ohmic loss design value for the V-2005 cavity is 0.8 kW/cm$^2$, which is reduced by 24% compared to the V-2003 cavity while maintaining the same theoretical efficiency. The new cavity design parameters are shown in Table II and the cavity profile and axial electric field profile are shown in Fig. 2. For comparison, the V-2003 cavity has an uptaper of 1.2°, a straight section length of 1.8 cm, and a downtaper angle of 2.5°. In each case, the final cavity design included additional nonlinear output uptapers, which were designed using CASCADE. The V-2005 cavity was fabricated by electroforming with a tolerance of better than 0.01 mm (0.4 mil).

### III. EXPERIMENTAL SETUP

The 110 GHz, 1.5 MW gyrotron oscillator schematic is shown in Fig. 3 in the axial configuration (without an internal mode converter). A diode Magnetron Injection Gun

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**TABLE I. Nominal design parameters for the gyrotron.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>110 GHz</td>
</tr>
<tr>
<td>Microwave power</td>
<td>1.5 MW</td>
</tr>
<tr>
<td>Beam voltage</td>
<td>96 kV</td>
</tr>
<tr>
<td>Beam current</td>
<td>40 A</td>
</tr>
<tr>
<td>Beam alpha ($\alpha=\nu_m/l$)</td>
<td>1.4</td>
</tr>
<tr>
<td>Operating mode</td>
<td>TE$_{22,6}$</td>
</tr>
<tr>
<td>Pulse length</td>
<td>3 $\mu$s</td>
</tr>
<tr>
<td>Cavity magnetic field</td>
<td>4.3 T</td>
</tr>
</tbody>
</table>

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**TABLE II. V-2005 cavity parameters.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input taper</td>
<td>2.5°</td>
</tr>
<tr>
<td>Straight section length</td>
<td>1.8 cm</td>
</tr>
<tr>
<td>Output taper</td>
<td>0.7°</td>
</tr>
<tr>
<td>Mode purity</td>
<td>99.78%</td>
</tr>
<tr>
<td>Frequency</td>
<td>110.069 GHz</td>
</tr>
<tr>
<td>$Q$ factor</td>
<td>837</td>
</tr>
<tr>
<td>Peak ohmic loading</td>
<td>0.8 kW/cm$^2$</td>
</tr>
<tr>
<td>Normalized length ($\mu$)</td>
<td>16.1</td>
</tr>
<tr>
<td>Power (triplet)</td>
<td>1.62 MW</td>
</tr>
<tr>
<td>Power (triplet, velocity spread 5%)</td>
<td>1.4 MW</td>
</tr>
</tbody>
</table>
(MIG) nominally operated at 96 kV and 40 A is used to form an electron beam of 1.0 cm radius in the cavity. A superconducting magnet is used to generate the 4.3 T field needed for operation at 110 GHz. The electron beam radius as well as the electron velocity ratio ($\alpha$) can be fine-tuned by a room-temperature copper coil (referred to as the gun coil) by altering the field at the cathode to change the compression ratio. The microwave radiation generated in the cavity is brought to the 3.91 mm thick, fused quartz window through a 2.23 cm radius cylindrical waveguide, which also serves as the collector for the spent electron beam. The velocity pitch factor of the beam ($\alpha = v_L/v_0$) was measured using a cylindrical probe located near the cavity. The probe can be calibrated in situ at low voltages to measure the axial velocity of the beam and then can be used to determine the transverse velocity at the operating voltage. The gyrotron was operated at up to 4 Hz repetition rate. The average output power was measured by dry calorimetry using a 20 cm diameter laser calorimeter modified as described in Ref. 16. A correction was made for the reflectivity of the calorimeter surface at 110 GHz. The microwave pulse shape was recorded using a broadband video detector.

The frequencies were measured using a heterodyne receiver that mixes the gyrotron signal with a harmonic of an 8–18 GHz local oscillator signal from a YIG oscillator. The resulting IF signal was band-limited between 150 and 500 MHz and was fast Fourier analyzed on a digital oscilloscope to display the sidebands.

IV. EXPERIMENTAL RESULTS

The V-2005 cavity was fabricated and installed in the axial configuration to verify its performance. Figure 4 shows the results of power measurements of various modes around the design mode, TE$_{22,6}$, as a function of main magnetic field. The voltage and current were maintained near 97 kV and 40 A during these measurements. A maximum power of 1.67 MW was measured at 97 kV and 41 A in the TE$_{22,6}$ design mode. The beam velocity pitch factor was measured to be 1.35 at this point. The power at other points in Fig. 4 was optimized by changing the cathode magnetic field to adjust the beam radius and alpha. The maximum power measured in the TE$_{24,5}$ mode was 1.51 MW corresponding to an efficiency of 39%. At high main magnetic fields, the TE$_{20,7}$ and TE$_{23,6}$ modes are excited at different beam compression regimes, that is, different values of magnetic field at the cathode. The maximum power at the TE$_{20,7}$ mode is 1.33 MW. We estimate that the power measurements are accurate to ±5% on an absolute scale.

The frequencies of various modes were compared with the theoretical calculations performed using a cold cavity code. The results are shown in Table III. The measured fre-

![FIG. 2. V-2005 cavity axial electric field (top) simulated by MAGY and cavity geometry profile (bottom).](image)

![FIG. 3. 1.5 MW, 110 GHz gyrotron experiment schematic in axial configuration.](image)

![FIG. 4. Power as a function of magnetic field at various modes in the V-2005 cavity. The beam voltage is 97 kV and the current is 40 A.](image)

<table>
<thead>
<tr>
<th>Mode</th>
<th>$f_{\text{exp}}$ (GHz)</th>
<th>$f_{\text{calc}}$ (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE$_{24,5}$</td>
<td>107.10</td>
<td>107.055</td>
</tr>
<tr>
<td>TE$_{21,6}$</td>
<td>107.17</td>
<td>107.128</td>
</tr>
<tr>
<td>TE$_{22,6}$</td>
<td>110.05</td>
<td>110.069</td>
</tr>
<tr>
<td>TE$_{20,7}$</td>
<td>112.65</td>
<td>112.630</td>
</tr>
<tr>
<td>TE$_{23,6}$</td>
<td>113.00</td>
<td>113.001</td>
</tr>
</tbody>
</table>
frequencies are in good agreement with the calculated frequencies with a difference of ±45 MHz.

To investigate the excitation regime of various modes, a mode map was generated by varying the cathode magnetic field and the main magnetic field while holding the voltage and current fixed near 97 kV and 40 A, respectively. In the course of the generation of the mode map, both the gun magnetic field and the main magnetic field were adjusted. Lower values of the gun field at a fixed value of the main magnetic field resulted in a smaller beam radius in the cavity and higher velocity pitch factor, which eventually led to reflection of the beam toward the gun. Higher values of the gun magnetic field at a fixed value of the main magnetic field result in larger beam radius and eventually led to beam interception in the tube. The mode map is shown in Fig. 5. From Fig. 5 we see a fairly wide region over which the design mode $\text{TE}_{22,6}$ is excited. The highest efficiency point is found as expected at lower values of magnetic field. For comparison, the mode map of the V-2003 cavity was measured using the identical experimental system and methods, with the results shown in Fig. 6. These results are in very good agreement with our previous results for the same cavity, published in Ref. 1, as expected.

An interesting difference in the operation of the two cavities is the absence of the excitation of the counter-rotating $\text{TE}_{19,7}$ mode in the mode map of the V-2005 cavity. As seen in Fig. 6, for the V-2003 cavity, the $\text{TE}_{19,7}$ mode is excited near the $\text{TE}_{22,6}$ mode regime at lower values of main magnetic field and gun magnetic field. This prevents access to the high efficiency regime of the $\text{TE}_{22,6}$ design mode. In the V-2003 cavity, a series of $\text{TE}_{m,n}$ modes is excited, including a small region of the $\text{TE}_{18,7}$ mode and a wide region of the $\text{TE}_{20,7}$ mode. The $\text{TE}_{m,n}$ modes are not seen in the V-2005 cavity mode map. This effect is explained in Sec. V by a startup scenario analysis of both the V-2005 and V-2003 cavities.

Figure 7 shows a power comparison as a function of magnetic field for the V-2003 and V-2005 cavities. The highest power produced in the V-2003 cavity was 1.43 MW with an efficiency of 37%. This result is nearly identical to our previous results published in Ref. 1. The highest power produced in the V-2005 cavity was 1.67 MW with an efficiency of 42% in the $\text{TE}_{22,6}$ mode. It is evident from Fig. 7 that the V-2005 cavity demonstrates higher power and efficiency than the V-2003 cavity. The efficiency in the V-2005 cavity was increased from 37% to 42% compared to the V-2003 cavity, a major improvement.

V. STARTUP SCENARIO ANALYSIS

A very interesting feature of the above experimental results is that a slight change in the uptaper angle between the two cavities resulted in a significant change of mode competition. In this section, we analyze the mode competition and startup scenarios of the $\text{TE}_{22,6}$ and the $\text{TE}_{19,7}$ modes in both the V-2003 and V-2005 cavities. It is well known that the...
Experimental results for a 1.5 MW, 110 GHz gyrotron
ally called the coupling coefficient. Equation nonuniform magnetic field, finite radial thickness of the elec-
alized start current equation taking into account the
quality factor accounting for ohmic and diffractive
overmoded gyrotron is19

![Diagram of field amplitude and phase profiles](image)

**FIG. 8.** (a) Normalized field amplitude (upper) and phase profile (bottom) of cold-cavity MAGY simulation for the V-2005 cavity (solid line is the TE22,6 mode and dashed line is the TE19,7 mode). (b) Normalized field (upper) and phase profile (bottom) of cold-cavity MAGY simulation for the V-2005 cavity (solid line is the TE22,6 mode and dashed line is the TE19,7 mode).

sequence of the mode startup is vital in deciding the eventual dominant mode.17,18 By studying the relative values of start current of the two modes during the evolution of the voltage, current, and alpha, we can predict the eventual dominant mode. The generalized equation for the start current in an

\[ I_b^* = \frac{2\pi mc^3 \gamma_0/e}{1/L} \int_0^L |f(z)|^2 dz \]

\[ \left[ s'/(2s^2) \right] Q \int W_\beta(\beta_{\pm 0}) \beta_0^{l(\pm 3)}(\chi' G) r_b d\beta_{\pm 0} \]

where \( s \) is the cyclotron resonance harmonic number, \( Q \) is the quality factor accounting for ohmic and diffractive losses, \( \beta_{\pm 0} \) is the initial orbital electron velocity normalized to the speed of light, \( r_b \) is the electron guiding center radius, and the function \( f(z) \) describes the axial structure of the resonant electric field. \( G(r_b) = J_{m-2}(k_1 r_b)/(v^2 - m^2)J_m(v) \) is usually called the coupling coefficient. Equation (2) is a general-
alized start current equation taking into account the nonuniform magnetic field, finite radial thickness of the elec-
tron beam, and velocity spread of the beam. \( W_\beta \) describes the distribution function for the velocity spread and \( \chi' \) is the imaginary part of the linearized dielectric susceptibility of an electron beam. In our analysis, we have assumed an ideal beam with no radial spread in guiding centers and no veloc-
ity spread. The actual measured magnetic field profile is used in the simulations. In order to simulate the start current, the electric field profile magnitudes and phases at each mode (the TE22,6 and TE19,7 modes) were generated using MAGY in the absence of the electron beam as shown in Fig. 8.

Figure 9 shows the coupling coefficients of the TE22,6 and TE19,7 modes. The beam radius is normalized to the cavity wall radius. The TE22,6 mode couples strongly to the electron beam for normalized beam radii values between 0.5 and 0.55. As the normalized beam radius is decreased below 0.5, the TE19,7 mode has a stronger coupling and so it is likely that the TE19,7 mode will be excited and will eventually dominate over the TE22,6 design mode. From this simple coupling coefficient calculation, we can see that the beam radius can help to determine the eventual dominant mode.

Figure 10 shows the start current for the TE22,6 and TE19,7 modes for various values of beam radius as the beam voltage, current, and alpha evolve during the startup. The start current contour plots at \( I_0 = 40 \) A as a function of beam alpha and beam voltage were generated for the TE22,6 and TE19,7 modes. The competing TE22,6 and TE19,7 modes are excited in the region within the solid (TE22,6) and the dashed (TE19,7) curves in each plot. The plot also shows the evolution of the beam velocity pitch factor \( \alpha \) with voltage calculated using an adiabatic theory as follows:

\[ \alpha = \left( \frac{v^2 - 1}{\gamma^2 \beta_{\perp}^2 - 1} \right)^{-1/2} \]

where \( \gamma \) is the relativistic factor and \( \beta_{\perp} \) is the perpendicular velocity normalized to the velocity of light, and it is ex-
pressed by

**FIG. 9.** Coupling coefficient of the TE22,6 mode and TE19,7 mode. \( r_b \) is the beam radius and \( a \) is the cavity radius.
\[ \beta_1 = \left( \frac{E_g}{c B_g} \right) \left( \frac{B_0}{B_g} \right)^{1/2} \]

\( E_g \) and \( B_g \) are the electric and magnetic fields at the gun cathode and \( B_0 \) is the cavity magnetic field. The adiabatic behavior of the electron gun pitch factor versus beam voltage given in Eq. (3) was verified by runs of a simulation code EGUN. The plots are obtained at values of the normalized beam radius of 0.52, 0.505, and 0.48. Figure 10 shows the results for the V-2005 and V-2003 cavities. It is seen that the startup path versus beam voltage moves into the excitation region of the \( \text{TE}_{22,6} \) mode first, and then the \( \text{TE}_{19,7} \) mode for \( r_b = 0.52a \) for both cavities. However, in the V-2003 cavity, the start current contours of the \( \text{TE}_{22,6} \) mode and the \( \text{TE}_{19,7} \) mode overlap each other at the beam radius \( r_b = 0.505a \). In contrast the beam curve passes the \( \text{TE}_{22,6} \) mode start current contour line first for a beam radius \( r_b = 0.505a \) in the V-2005 cavity. For this cavity, even at \( r_b = 0.48a \), the \( \text{TE}_{22,6} \) mode wins over the \( \text{TE}_{19,7} \) mode. However, in the V-2003 cavity, the \( \text{TE}_{19,7} \) start current curve is intersected first for \( r_b = 0.48a \), which likely leads to stable \( \text{TE}_{19,7} \) mode excitation. We see from Fig. 10 in general the margin between the excitation of the \( \text{TE}_{22,6} \) and the \( \text{TE}_{19,7} \) modes is smaller in the V-2003 cavity when compared to the V-2005 cavity. This can explain the easy excitation of the competing \( \text{TE}_{19,7} \) mode in the V-2003 cavity, which prevents access to the high efficiency regime of the \( \text{TE}_{22,6} \) mode.

FIG. 10. Iso-start current contour plot at \( I_s = 40 \) A in the alpha and beam voltage plane for different values of the beam radius. The solid line is the \( \text{TE}_{22,6} \) mode, the dashed line is the \( \text{TE}_{19,7} \) mode, and the dash-dot line is the evolution of the beam velocity pitch factor. (Electric fields and phases are obtained by MAGY simulation.) (a), (c), (e) V-2005 cavity: (a) \( r_b = 0.52a \), (c) \( r_b = 0.505a \), (e) \( r_b = 0.48a \). (b), (d), (f) V-2003 cavity: (b) \( r_b = 0.52a \), (d) \( r_b = 0.505a \), and (f) \( r_b = 0.48a \).\( a \) is the cavity radius.
startup scenario simulation strongly supports the experimental observation of different mode competition between the TE\textsubscript{22,6} and TE\textsubscript{19,7} modes in the two cavities that were investigated.

VI. CONCLUSIONS

We have presented results for a cavity with reduced ohmic losses and have compared them to those from an earlier cavity. Higher power and efficiency were obtained using the low ohmic loss cavity when compared to the previous cavity. Since the power measurements were made in the same experimental system with only the cavities interchanged, the measured efficiency difference may be reported with very high confidence. The primary reason for the increase in power and efficiency in the new cavity is the cavity profile, which changes the startup scenario as discussed in detail in Sec. V. The absence of competition from the TE\textsubscript{19,7} mode allows access to the higher efficiency regime of the operating TE\textsubscript{22,6} mode. Up to 1.67 MW of power was measured at an efficiency of 42\%, which is a significant improvement over the 37\% efficiency measured with the previous cavity. The experimental results from this work suggest that a careful design of the cavity to ensure that the operating mode has a fairly wide range of excitation without competition from parasitic modes can lead to a major advantage in increasing the efficiency of the device.

The promising results from the low ohmic loss cavity experiments justify further investigation of the feasibility of using such a cavity in the 1.5–2 MW class of gyrotrons at 110 GHz.

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