Development of High Power Gyrotrons for Advanced Fusion Devices and DEMO

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Abstract

Megawatt (MW) gyrotrons, with a wide frequency range from 14 to 300 GHz, are developed in a collaborative electron cyclotron heating (ECH) study for advanced fusion devices and a demonstration power plant (DEMO). (1) The detailed designs of a 14 GHz 1 MW gyrotron have begun for actual fabrication. For a 14 GHz RF beam with high divergence, a calculated transmission efficiency of 94% to the corrugated waveguide coupling position was initially obtained by minimizing the RF transmission path. (2) In the experimental tests of a new 28/35 GHz dual-frequency gyrotron, the cooling characteristics of an optimal-structure double-disk sapphire window was evaluated. We confirmed that operating at 0.4 MW with a continuous wave (CW) at 28 GHz is possible, which is twice the output power reported in previous studies. In the short pulse experimental test, the maximum powers of 1.65 MW at 28.04 GHz and 1.21 MW at 34.83 GHz were achieved. (3) The design study of a 77/51 GHz dual-frequency gyrotron was performed. The oscillations above 1.5 MW for 77 GHz and 1.3 MW for 51.88 GHz are expected with an electron beam pitch factor $\alpha = 1$ for a beam voltage $V_k = 80$ kV and beam current $I_k = 60$ A. (4) In an experiment with a 300 GHz gyrotron, the influence of the reflected wave from the window was reduced by tilting the output window, and the mode competition in the cavity was suppressed. An output power of 0.62 MW with a pulse width of 1 ms, which is the new record in this frequency, was obtained. We have also performed the first trial design study of a 240 GHz gyrotron for DEMO.

1. INTRODUCTION

Electron cyclotron heating (ECH), electron cyclotron current drive (ECCD), and electron Bernstein wave (EBW) heating are attractive and promising schemes for performing heating, current drive, and plasma control in fusion magnetic confinement systems, especially in future dense and large-core plasma control devices. Gyrotrons are powerful and essential tools for ECH and ECCD. At the University of Tsukuba, Megawatt (MW)-class gyrotrons, that cover a wide frequency range (14 to 300 GHz), are currently being developed in collaboration with several research organizations and universities, for present and future demonstration power plant (DEMO) fusion devices.
as shown in Fig.1. Each open bar represents the design target of the output power. Each hatched bar represents the achieved output power in long pulse operation longer than 1 s, along with the obtained pulse width. Each filled bar represents the achieved output power in ms operation. Design parameters of 14 GHz gyrotron, 28/35 GHz dual-frequency gyrotron, and 77/51 GHz dual-frequency gyrotron are shown in Table 1.

In the relatively low-frequency region of 14-35 GHz, there are different technical problems compared with high-frequency gyrotrons because the wavelength used is long and the divergence of the RF beam is large. In particular, 14 GHz gyrotron have special characteristics and had not been developed until now. The development of MW gyrotrons in this low-frequency range and their applications in advanced nuclear fusion devices like the Q-sh u University Experiments with Steady-State Spherical Tokamak (QUEST) and the GAMMA 10/PDX is useful for nuclear fusion research.

With the collaboration between the University of Tsukuba and Kyushu University, the 28 GHz gyrotron developed for GAMMA 10/PDX of the University of Tsukuba, which achieved an output power of 1.38 MW, is being used in the QUEST plasma experiment campaign [1,2]. An unprecedented EC-driven plasma current of 80 kA level was non-inductively achieved via a 28 GHz injection [3]. These successful results lead to a 28 GHz gyrotron application program at the National Spherical Torus Experiment (NSTX-U) of the Princeton Plasma Physics Laboratory (PPPL) [4]. During the experimental tests of the new 28/35 GHz dual-frequency gyrotron (2 MW for 3 s and 0.4 MW CW) conducted in 2016, main-mode oscillations were observed at frequencies of 28.036 and 34.831 GHz with an output power of 1.27 and 0.48 MW, respectively. A total efficiency of 50% was achieved at a 28 GHz operation [1].

The joint program between the National Institute for Fusion Science (NIFS) and the University of Tsukuba developed three 77 GHz and two 154 GHz gyrotrons for large helical device (LHD). Typically, the 77 GHz gyrotrons achieved a maximum output power of 1.9 MW and a quasi-CW (continuous wave) 75-min-long operation at 0.22 MW. The 154 GHz gyrotrons achieved a maximum output power of 1.25 MW and a 30-min-long operation at 0.35 MW. A total plasma injection power of 5.4 MW was achieved using these gyrotrons. Gyrotrons have contributed to the enhancement of the LHD plasma performance in recent electron internal transport barrier (ITB) experiments. By combining high power ECH and neutral beam injection (NBI), high temperature plasmas with simultaneous high electron temperature (7–9 keV) and ion temperature (4–6 keV) have been obtained. A steady-state plasma with a line-averaged electron density of $1 \times 10^{19}$ m$^{-3}$ and electron temperature of 3.5 keV was sustained for 330 s. For the next step of development of NIFS gyrotrons, a design study has been started for 154 and 116 GHz dual-frequency gyrotron to expand the range of the LHD plasma parameters [5–8].

The development of a 300 GHz gyrotron for ECH and ECCD in the DEMO is currently in progress in collaboration with National Institutes for Quantum and Radiological Science and Technology (QST). During short-pulse test tube experiments performed until 2016, an output power exceeding 0.52 MW was achieved for the single $T_{E32,18}$ mode. This gyrotron is a conventional type without a built-in mode converter. Seven oscillations were obtained in the 226–254 GHz frequency range. In addition, reflection from the output window was observed to affect the oscillation mode characteristics [1].

![FIG.1. Development of over-MW gyrotrons for fusion for frequencies from 14 GHz to sub-terahertz. The output powers achieved during the short- and long-pulse operation are shown, along with the corresponding pulse width. Their designed output powers are also shown.](image-url)
TABLE 1. DESIGN PARAMETERS OF TSUKUBA GYROTRONS

<table>
<thead>
<tr>
<th></th>
<th>14 GHz Gyrotron</th>
<th>28/35 GHz Dual-frequency Gyrotron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>14 GHz</td>
<td>28 GHz</td>
</tr>
<tr>
<td>Output Power</td>
<td>&gt; 1 MW</td>
<td>2 MW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.4 MW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 MW</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>&gt; 5 s</td>
<td>3 s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 s</td>
</tr>
<tr>
<td>Output Efficiency</td>
<td>35% (with CPD)</td>
<td>50% (with CPD)</td>
</tr>
<tr>
<td>Beam Voltage</td>
<td>75-80 kV</td>
<td>80 kV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>70 kV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80 kV</td>
</tr>
<tr>
<td>Beam Current</td>
<td>50 A</td>
<td>70 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40 A</td>
</tr>
<tr>
<td>MIG</td>
<td>triode</td>
<td>triode</td>
</tr>
<tr>
<td>Cavity Mode</td>
<td>TE_{4,2}</td>
<td>TE_{8,5}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TE_{10,6}</td>
</tr>
<tr>
<td>Output Mode</td>
<td>HE_{1,1} waveguide mode</td>
<td>Gaussian-like</td>
</tr>
<tr>
<td>Output Window</td>
<td>Sapphire Double Disk</td>
<td>Sapphire Double Disk</td>
</tr>
<tr>
<td>Collector</td>
<td>Depressed Collector</td>
<td>Depressed Collector</td>
</tr>
<tr>
<td>Sweeping Coils</td>
<td></td>
<td>Sweeping Coils</td>
</tr>
</tbody>
</table>

CPD : Collector Potential Depression

In this paper, section 2 describes the design study of 14 GHz gyrotron. The experimental results of the novel 28/35 GHz dual-frequency gyrotron are presented in section 3. The design of a novel 77/51 GHz dual-frequency gyrotron is discussed in section 4. The experimental results of the 300 GHz gyrotron and the trial design study of 240 GHz gyrotron for the DEMO are shown in section 5.

2. DEVELOPMENT OF THE 14 GHz GYROTRON

Fabrication designs for a novel 14 GHz 1MW gyrotron, which has not ever been developed, were started. First, we studied a 14/28 GHz and a 14/21 GHz dual-frequency gyrotron. However, there were no possible combinations of cavity oscillation modes due to the low frequency. Therefore, we selected a single oscillation in TE_{4,2} mode. The design parameters of 14 GHz gyrotron are shown in Table 1. The output power is superior to 1 MW for a pulse width superior to 5 s. The same superconducting magnet (SCM) with a bore diameter of 350 mm is used in the 28GHz and 77GHz gyrotron operations.

The magnetron injection gun (MIG) is a triode type, it can controlled the electron beam parameters. The cathode diameter was decided to be smaller than for the other gyrotron (75 mm instead of 95 mm) as the magnetic field strength is lower at the MIG region. An electron beam pitch factor \( \alpha \) of 1.0 was obtained at an anode voltage of 41 kV for a beam voltage \( V_k = 80 \) kV and beam current \( I_k = 50 \) A. The calculated dependency of the cavity oscillation power on the beam current at 14 GHz is shown in Fig. 2(a). Oscillations above 1.2 MW are expected with \( \alpha = 1 \) for \( V_k = 80 \) kV and \( I_k = 50 \) A. A time evolution of a double-disk sapphire window temperature calculated with the experimental results for a 28 GHz gyrotron window (described in section 3) is shown in Fig. 2(b). This result suggests that 1 MW CW operation at 14 GHz will be possible by installing a double-disk sapphire window.

![FIG.2. Calculation results of the 14 GHz gyrotron. (a) Beam current dependencies of the cavity oscillation power. (b) Time dependency of the double disk window temperatures.](image-url)
Because 14 GHz RF beams have a high divergence, the calculated RF transmission efficiency from the mode converter to the output window was 69% with the same inner mirror configuration as the 28 GHz gyrotron. Usually, the profile and the phase of an output RF beam are adjusted using a matching optics unit (MOU), and the beam is coupled to a corrugated waveguide in the HE_{11} mode. Therefore, the transmission efficiency of the RF beam greatly decreases along the long optical path length between the last internal mirror and the MOU mirror. The structural cross sections of the 28 GHz gyrotron and new designed 14 GHz gyrotron are shown in Fig. 3, with the RF beam profile at coupling position. A calculated transmission efficiency of 94 % from the mode converter to the corrugated waveguide coupling position was obtained by minimizing the RF transmission path. This was achieved by inserting the coupling position into the gyrotron, adjusting the mirrors position, and increasing the mirrors size. Further improvements of transmission efficiency are expected by optimizing the mirror arrangement and using a corrugated horn antenna. As this design does not require a MOU connecting the gyrotron and the waveguide, the production cost of this gyrotron system will be low.

The fabrication of the 14 GHz gyrotron has been started, using common parts that have already been produced for the 28 GHz gyrotron.

![RF transmission design of the 14 GHz gyrotron](image)

3. DEVELOPMENT OF THE 28/35 GHz DUAL-FREQUENCY GYROTRON

During the experimental tests conducted in 2017, the cooling characteristics of a double-disk sapphire window were evaluated. High-power gyrotron windows are generally made of diamond disk. However, the divergence of an RF beam is large at lower frequencies, hence requiring a diamond disk of large diameter. As the wavelength increases, a thicker disk is necessary to achieve frequency matching. These diamond disks are difficult to manufacture and very expensive. For this reason, this gyrotron has been designed with a double-disk sapphire window.

Temperature evolution at the center of the output window, i.e., the temperature increase during oscillations of 2 s at 0.45 MW, and the temperature decrease after oscillation, were measured using an infrared (IR) camera. The time dependencies of the sapphire disk temperature for each flow rate of a fluorocarbon coolant (FC-3283) are...
shown in Fig. 4(a). The higher coolant flow rate, the faster the temperature decrease time was. As shown in Fig. 4(b), the values of the heat transfer coefficient versus the flow rate of the double-disk window coolant were estimated by comparing the calculation results with the experimental measurements in 2 s or later. The calculated window temperature saturated at about 80 °C, with an output power of 0.4 MW and a heat transfer coefficient of 1500 W/m²K. We confirmed that operation at 0.4 MW, which is two times the output power reported in previous studies, with CW operation at 28 GHz is possible with a coolant flow rate higher than 30 L/min. High power CW operation of low frequency gyrotrons is very important due to their potential as heating sources in spherical tokamaks, such as QUEST.

During the experimental tests conducted in 2016, the output power at 34.8 GHz was only 0.48 MW, due to the limit of the anode power supply. Therefore, the electron gun was remodeled to obtain a higher-power at both frequencies. The dependences of the output power and efficiency of the 28.04 GHz and 34.83 GHz oscillation on the beam current are shown in Fig. 5(a) and 5(b), respectively. An output power of 1.65 MW was achieved at 28.04 GHz, with a beam voltage $V_k$ of 80 kV and an anode voltage $V_{ak}$ of 26.7 kV. Similarly, an output power of 1.21 MW at 34.83 GHz was obtained with $V_k = 80$ kV and $V_{ak} = 37.7$ kV.

The high-power RF transmission test at 28 GHz for the plasma heating and the quasi-CW operation test will be performed as the next step of this experiment.

**FIG.4.** Experimental test of the double disk window with an output power of 0.45 MW 2 s at 28 GHz. (a) Time dependency of the double disk window temperatures. (b) Flow rate dependency of the heat transfer coefficient of the double disk window.

**FIG.5.** Beam current dependencies on the experimental obtained output powers and efficiencies (a) at 28.04 GHz and (b) 34.83 GHz.

4. DEVELOPMENT OF THE 77/51 GHz DUAL-FREQUENCY GYROTRON

A design study of a 77/51 GHz dual-frequency gyrotron was started for plasma start-up in an experiment with deuterium plasma on the LHD. In the design of the dual-frequency gyrotron, the combination of cavity oscillation
modes for the two frequencies \( f_1 \) and \( f_2 \) must be able to exist in the same cavity structure. The difference between the radiation angles of the \( f_1 = 77 \) GHz and \( f_2 = 51 \) GHz cavity modes must be approximately 0° to achieve a high RF beam transmission efficiency for both modes using the same internal mirrors. It is necessary to have frequency matching for the diamond window with the same thickness at the both frequencies. In addition, under the magnetic field distribution produced by the SCM, a MIG is required to inject the electron beam at the first peak of the cavity electric field for both oscillation modes with a pitch factor \( \alpha = 1.0–1.2 \).

Using the same cavity structure as the existing 77 GHz gyrotron (TE\(_{18,7} \) mode), an oscillation power of 1.3 MW is expected in the 49.69 GHz TE\(_{12,4} \) mode. The difference between the radiation angles of the two cavity modes is 0.96°. Using the same radiator and mirrors system as the existing 77 GHz gyrotron, the transmission efficiency of a 49.69 GHz RF beam to the output window is expected to be 91%. By changing the existing diamond thickness from 1.64 mm to 2.45 mm, the power reflectance is 0% at 77 GHz and 3.6% at 49.69 GHz. By replacing only the window of the existing 77 GHz gyrotron, this combination of oscillation modes can operate for several seconds with two frequencies of 77 and 51 GHz. However, a long pulse operation will be difficult due to the transmission loss of the RF beam and the reflection from the window.

We selected the following new combination of cavity oscillation modes: TE\(_{18,7} \) with \( f_1 = 77 \) GHz and TE\(_{12,5} \) with \( f_2 = 51.88 \) GHz. The difference between the radiation angles of the both cavity modes is 0.24°. The calculated dependencies of the cavity oscillation power and efficiency on the beam current at 77 and 51.88 GHz are shown in Fig. 6(a) and 6(b), respectively. The oscillations above 1.5 MW for 77 GHz and 1.3 MW for 51.88 GHz are expected with an electron beam pitch factor \( \alpha = 1 \) for \( V_k = 80 \) kV, and \( I_k = 60 \) A. The design of the triode MIG is the same as the one used for the 77 GHz and 154 GHz gyrotrons, which is advantageous for fabrication process. From the dependences of the pitch factor \( \alpha \) and its spread \( \Delta \alpha/\alpha \) on the anode voltage, the MIG is expected to operate at both 77 and 51.88 GHz frequencies with \( \alpha = 1–1.2 \) and \( \Delta \alpha/\alpha < 5 \% \) at \( V_k = 80 \) kV and \( I_k = 60 \) A, indicating highly efficient oscillations inside the cavity. The reflectance of the diamond window with 2.45 mm thickness is 0% at 77 GHz and 0.5% at 51.88 GHz. The RF transmission loss power is small and the CW operation will be expected in this combination of cavity oscillation modes.

5. DEVELOPMENT OF THE SUB-TERAHERTZ GYROTRON FOR DEMO

Performance test of the 300 GHz short-pulse test tube has been performed in the collaboration between the University of Tsukuba and the OST. In the previous experiments, the reflection from the output window was observed to affect the oscillation mode characteristics. By changing the reflectance of the output window by adding the SiO2 disk to the window, the competing mode oscillation was suppressed and the main mode oscillation was obtained [1].

During the experiment conducted in 2017, the influence of the reflected wave from the window, which increases the effective Q value of the cavity for the competing mode, was reduced by changing the inclination of the output sapphire window, and mode competition in the cavity was suppressed. Figure 7 shows (a) a photograph of oscillation test setup, (b) its structural cross-section view, (c) a photograph of the 300 GHz gyrotron, and (d) detail structural cross-sectional view of the window region with the window tilting structure. This is a conventional type
gyrotron, without a built-in mode converter. The cavity oscillation mode $\text{TE}_{32,18}$ is a very high mode to operate with a MW-level power and long pulses. The electron gun is a diode gun, the output window is a single disk sapphire window with a thickness of 2.79 mm and the overall length of the gyrotron is 1987 mm. A SCM with a bore diameter of 110 mm produces a strong 13 T magnetic field. The gyrotron was remodeled to be able to tilt the window by adding a bellows between the window and the collector. By tilting the window, the reflection of the waveguide mode of $\text{TE}_{mn}$ was changed.

The dependences of the output power on the beam current are shown in Fig. 8. Crossed circles indicate the output power when the tilting window angle is $1.15^\circ$, and crossed diamonds indicate the output power with SiO$_2$ disk. An output power of 0.62 MW with a pulse width of 1 ms, which is the highest reported power at this frequency, was obtained. The influence of the window reflection will be removed by installing a built-in mode converter. This is because a mode converter cannot radiate a counter-rotating mode as a Gaussian beam or the cavity oscillation mode at a different radiation angle at the mode converter cannot return to the cavity as a circular waveguide mode. The obtained non-saturated power of over 0.6 MW with a high-order volume mode oscillation in the sub-terahertz region gives an important impact on the development of gyrotrons for DEMO.

**FIG. 7.** Tilting structure of the 300 GHz gyrotron output window: (a) Photograph of the oscillation test setup, (b) structural cross-section of the 300 GHz gyrotron, (c) photograph of the 300 GHz gyrotron, and (d) structural cross-section of the window tilting structure.

**FIG. 8.** Beam current dependencies of output power. By reducing the influence of the reflected wave from the window, mode competition in the cavity was suppressed. An output power of 0.62 MW was obtained.
We considered the assembly of a mode convertor, with a calculated transfer efficiency of about 98% in the 300 GHz test tube. However, this was impossible due to the bore diameter of the present SCM and the electron beam clearance. A 220-250 GHz gyrotron is currently being studied for tokamak- or helical-type DEMO. We have also performed the first trial design study of a 240 GHz gyrotron. The bore diameter of SCM is 240 mm based on the trial design of 10 T SCM. This SCM bore diameter allows the installation of a built-in mode convertor. The trial designs of the cavity were performed with the same oscillation mode of TE\textsubscript{32,18} as for the 300 GHz test tube, and the highest oscillation mode of TE\textsubscript{38,18}. Oscillations of 200 and 160 GHz were also studied in the structure of 240 GHz cavity resonator, as they have correspondence to the frequencies obtained for a diamond window with the thickness of 1.574 mm, similarly to 240 GHz. For both TE\textsubscript{32,18} and TE\textsubscript{38,18} modes at 240 GHz, an oscillation power of approximately 1.5 MW is expected with $V_k = 80$ kV, $I_k = 60$ A, and $\alpha = 1.0$. In addition, a 200 GHz oscillation power of 1 MW is expected with $V_k = 80$ kV, $I_k = 50$ A, and $\alpha = 1.0$. A trial design of MIG was performed using the magnetic field structure of the SCM trial design. Emission belt structure of the cathode was the same as for the 154 GHz gyrotron. The electron beam parameters of $\alpha > 1.0$ were obtained with a low $\alpha$ spread. The difference between the radiation angles of the 240 GHz TE\textsubscript{32,18} and 200 GHz TE\textsubscript{37,15} modes is 0.96°. The difference between the radiation angles of the 240 GHz TE\textsubscript{38,18} and 200 GHz TE\textsubscript{32,15} modes is 0.92°. Therefore, both combination of cavity oscillation modes will achieve a high RF beam transmission efficiency for both frequencies using the same internal mirrors.

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