Development of a High Power Gyrotron Operating at 28 and 35 GHz

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An experimental and design study has been commenced for a dual-frequency gyrotron (28 and 35 GHz). The target output power at 28 GHz is 2 MW. For a modified 28 GHz 1 MW gyrotron, an output power of 1.25 MW and operation of 0.6 MW for 2 s have been achieved at 28 GHz. For the 35.45 GHz oscillation test, a cavity oscillation power of 1.2 MW and an efficiency of 33.9% have been confirmed by considering the calculated transmission efficiency of 72%. These results support the development of dual-frequency gyrotrons for lower frequency ranges.

Keywords: dual-frequency (28 GHz and 35 GHz) gyrotron, oscillation test, mode converter, radiation angle, electron cyclotron heating

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A 28 GHz $TE_{8,3}$ oscillation mode gyrotron with a 1 MW output for 1 s has been developed as an upgrade for the GAMMA 10 Electron Cyclotron Heating (ECH) systems. For the initial short pulse experiment, a maximum power of 1.05 MW was obtained, which is in agreement with the design target value. In addition, a high efficiency of 40% without collector potential depression (CPD) was obtained at 0.8 MW [1].

Recent ECH physics experiments require 28 GHz gyrotrons for some plasma experimental devices. For the Q-shuUniversity Experimental with Steady-State Spherical Tokamak (QUEST) ECH system at Kyushu University, a 0.4 MW CW gyrotron is needed. For the ECH systems of GAMMA 10 and National Spherical Torus Experiment (NSTX) at Princeton Plasma Physics Laboratory (PPPL), a gyrotron with a 1.5 - 2 MW output for several seconds is required. Further, a 35 GHz gyrotron is required for the Helical-Axis Heliotron (Heliotron J) at Kyoto University. For consideration of the above test results and the requirements for gyrotron developments, an experimental and design study has been commenced for 28 and 35 GHz dual-frequency gyrotrons. If 35 GHz oscillations are possible in the 28 GHz gyrotron, it will be very useful for collaborative research.

For the 2012 experimental research, the electron gun and output window of the 28 GHz 1 MW gyrotron have been modified to improve the oscillation efficiency in high current regions and to perform the 35 GHz oscillation test. The improvement point of the Magnetron Injection Gun (MIG) design is that the cathode angle has been made deeper so that laminar flow is possible for the electron beam in front of the cathode. It is expected that a higher α operation with lower α dispersion and good laminar flow leads to higher oscillation efficiencies at higher beam currents. In the present cavity, with an oscillation mode of $TE_{8,3}$ at 28 GHz, $TE_{9,4}$ mode oscillation at 35.45 GHz can be achieved by changing the injection radius of the electron beam at the cavity. To minimize the output window reflection for both 28 and 35.45 GHz frequencies, the thickness of the sapphire disk has been modified from 3.49 to 6.94 mm. The calculated power reflection coefficient of the previous window is 65% at 35.45 GHz; it has been reduced to 2% at 35.45 GHz, while it remains constant at 1% for 28 GHz.

By implementing the MIG modifications, the saturation tendency of the 28 GHz oscillation efficiency at the beam current I_k between 40 and 50 A has been improved, and a 1.25 MW output power has been achieved at the beam voltage $V_k = 80$ kV, with $I_k = 50$ A. Operation at 0.6 MW for 2 s has been obtained. These results are expected to lead to the development of a 28 GHz, 2 MW gyrotron.

A preliminary test of the 35 GHz oscillation was performed using the modified 28 GHz, 1 MW gyrotron. The beam current (I_k) dependence of the output power P_o and its efficiency η are shown in Fig. 1. The P_o increases with an increasing I_k without reaching saturation. A P_o of 0.87 MW and a η of 24.4% have been obtained at V_k = 80 kV and I_k = 44.5 A. The calculated transmission efficiency at the output window from the cavity is about 72% at a 35.45 GHz oscillation. Considering this transmission

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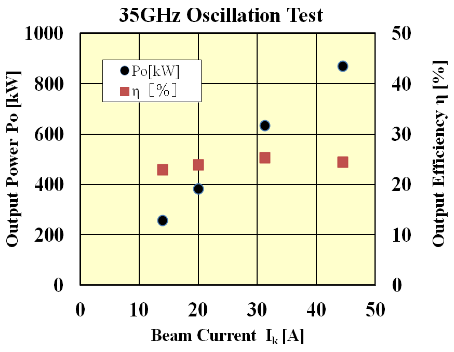
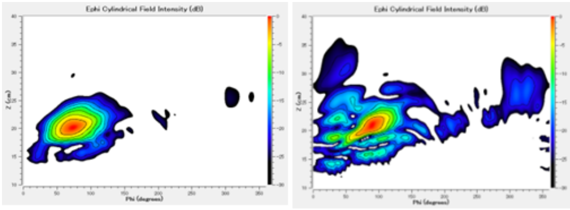
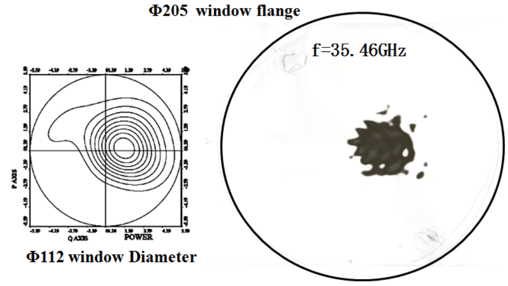


Fig. 1 Beam current dependence for output power and output efficiency (oscillation test results).



(a) 28GHz-TE$_{8,3}$ (b) 35.45GHz-TE$_{9,4}$

Fig. 2 Calculated radiated field patterns at r = 6 cm from the mode converter axis for (a) 28 GHz TE$_{8,3}$ and (b) 35.45 GHz TE$_{9,4}$.



(a) (b)

Fig. 3 (a) Calculated 35.45 GHz RF beam profile and (b) experimentally measured burn pattern at the output window.

efficiency, the experimental results indicate that the cavity oscillation power and efficiency are 1.2 MW and 33.9%, respectively. These results are similar to the results calculated by using the cavity code.

The RF transmission efficiency reduction at 35 GHz for the current gyrotron is caused by the radiation angle difference of the mode converter. The transverse radiation angle for the TE$_{m,n}$ mode can be described as [2]

$$\theta_{m,n} = N\cos^{-1}\left(\frac{m}{\chi_{m,n}}\right), \tag{1}$$

where the number of reflections N is 5 for the present mode converter. Thus, the difference in the radiation angle can be described as

$$\Delta\theta = N\left[\cos^{-1}\left(\frac{m1}{\chi_{m1,n1}}\right) - \cos^{-1}\left(\frac{m2}{\chi_{m2,n2}}\right)\right]. \tag{2}$$

The $\Delta\theta$ between the 28 GHz TE$_{8,3}$ mode and the 35.45 GHz TE$_{9,4}$ mode is 15.85°. The radiated field patterns at r = 6 cm from the mode converter axis are shown in Fig. 2 [3]. These results have been calculated using the electric field integral equation code SURF3D [4]. Figures 2 (a) and (b) shows the radiated field patterns from the 28 GHz TE$_{8,3}$ and 35.45 GHz TE$_{9,4}$ modes, respectively, with the present mode converter optimized for the 28 GHz TE$_{8,3}$ mode. The calculated 35.45 GHz RF beam profile at the output window is shown in Fig. 3 (a). Using a four-piece elliptical mirror system, the 35.45 GHz RF beam radiated from the mode converter is focused and transmitted to the outside of the tube through the output window. However, the transmission efficiency at 35.45 GHz is low (72%), and the peak power position of the RF beam shifts considerably from the center of the window, as shown in Fig. 3 (a), because the mode converter and mirror system are optimized for 28 GHz and not 35 GHz. The experimentally measured burn pattern of the RF beam at the output window is shown in Fig. 3 (b). The experimental results agree fairly well with the calculated ones, including the peak position of the RF power profile. Although the efficiency is degraded by approximately 30%, a significant power extraction is possible, since the modified window is transparent for both frequency ranges. The measured output RF frequency was 35.46 GHz. These results experimentally confirm the 35.46 GHz TE$_{9,4}$ mode oscillation in the cavity. By using the modified 28 GHz 1 MW gyrotron, it has been confirmed that the experimental results are consistent with the calculated results for a dual frequency gyrotron for lower frequency ranges. As the next step, a new design study of a 28 GHz higher power and dual-frequency gyrotron (28 GHz/35 GHz) has been commenced. The gyrotron uses a combination of TE$_{8,5}$ mode at 28 GHz and TE$_{10,6}$ mode at 34.77 GHz. This gives the smallest radiation angle difference of the mode converter.

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