New Power Records of Sub-Terahertz Gyrotron with Second-Harmonic Oscillation

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High-power sub-terahertz pulse gyrotrons are under development in FIR FU for application to collective Thomson scattering (CTS) measurement on fusion plasmas, especially on high-density plasmas such as those produced in LHD. Recently, we achieved a new power record of 62 kW at approximately 388 GHz with second-harmonic (SH) oscillation. Following this result, we modified the electron gun of the gyrotron to couple the electron beam more strongly to another oscillation mode that has a peak coupling coefficient two times as large as that of the 62 kW mode. Oscillation tests with the new mode attained higher power of 83 kW at about 389 GHz. These results constitute new second-harmonic-oscillation power records for sub-terahertz gyrotrons.

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In recent years, the development of vacuum electronic high-power sources in the terahertz band for application to various fields has intensified [1,2]. Gyrotrons have attained over one terahertz oscillations, at both second-harmonic (SH) and fundamental-harmonic (FH) oscillations [3, 4]. Therefore, sub-terahertz gyrotrons are very promising to diagnose high-density plasmas such as those produced in LHD. SH oscillation is attractive to relax the requirement for superconducting magnets. However, this approach may suffer the serious problem of mode competition with FH modes, especially when aiming for high output power. Thus, it is a challenge to realize a 100 kW-level sub-terahertz gyrotron as a power source for measurements by collective Thomson scattering [5–7]. In our previous work, we demonstrated greater than 50 kW SH oscillations at 350 GHz and about 40 kW SH oscillations at 390 GHz with a demountable-type first-stage gyrotron [8, 9]. In this paper, we report the significant progress achieved since then in SH oscillation of a sub-terahertz gyrotron.

To acheive high-power single-mode SH oscillation, it is very important to suppress mode competition. Figure 1 shows the distribution of Bessel prime zeros near candidate modes. The upper and lower numbers correspond to SH and FH resonances, respectively. This region has been carefully chosen so that the candidate SH modes are well isolated from the FH modes. It is also necessary to ensure self-consistency between the electron optics and the electron gun that are used in the present study. Thus, we selected the SH $TE_{1,8}$ and $TE_{17,2}$ modes because they are far from the neighboring FH $TE_{4,3}$ mode.

We fabricated a new sealed-off-type gyrotron, which operates in a pulsed mode. The pulse width is several microseconds and the repetition rate is less than 10 Hz. The cavity radius R_c of 2.99 mm leads to a resonance frequency f_c of about 388 GHz for the $TE_{1,8}$ mode and of about 389 GHz for the $TE_{17,2}$ mode. This cavity radius is also desirable to strongly couple the electron beam to the RF electric field in the cavity. Figure 2 shows the radial distribution of the coupling coefficients of the two modes. The electron beam enters the cavity whose radius $R_b \sim 1.8$ mm under conditions of typical design parameters. We then tested oscillation of the $TE_{1,8}$ mode. Since our gyrotron has no internal mode converter, the radiation is extracted as an oscillating mode along the direction of gyrotron axis through the output window [10].

After conditioning and adjusting the operation parameters, the $TE_{1,8}$ mode delivered 56 kW at a cathode voltage

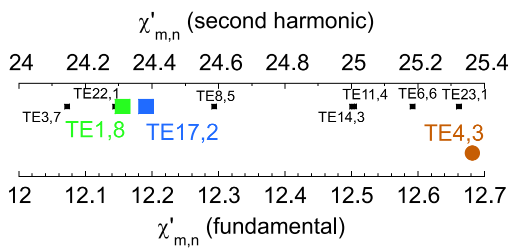

Fig. 1 Distribution of SH and FH modes.

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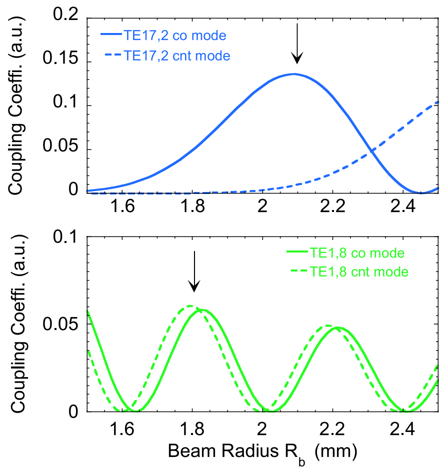

Fig. 2 Radial distribution of coupling coefficient of $TE_{17,2}$ and $TE_{1,8}$ modes.

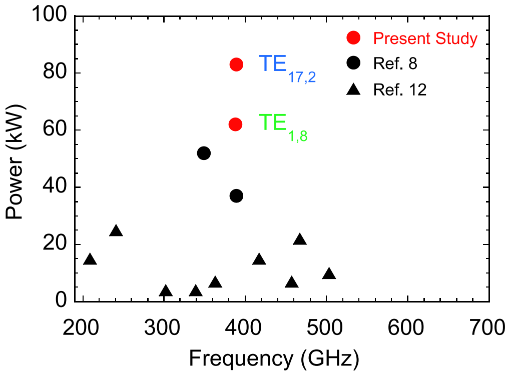

Fig. 3 Power records versus frequency.

V_k of 60 kV and a beam current I_b of 9 A. This power was measured with a water load located just outside the vacuum window. The oscillation frequency of 387.7 GHz, measured by a heterodyne receiver system, was almost equal to the resonance frequency f_c of the $TE_{1,8}$ mode. We then increased V_k to 65 kV to avoid power saturation with I_b. The output power reached 62 kW with I_b at 11 A, and we confirmed single-mode oscillation without the neighboring FH $TE_{4,3}$ mode for both cases [11]. However, we were again confronted by power saturation with I_b, which might be partly because of deterioration in beam quality at large current.

Another likely reason for the observed power saturation is the rather low coupling coefficient of the $TE_{1,8}$ mode at R_b = 1.8 mm. Therefore, we tried oscillation with the $TE_{17,2}$ mode, which has a larger peak coupling coefficient. However, in this case, the radius R_b necessary for peak coupling is about 2.1 mm. Hence, based on a design calculation [12], we modified the electron gun to meet this condition. Oscillation tests with this new electron gun achieved a higher power record of 83 kW with V_k = 60 kV and I_b = 10 A. The measured oscillation frequency of

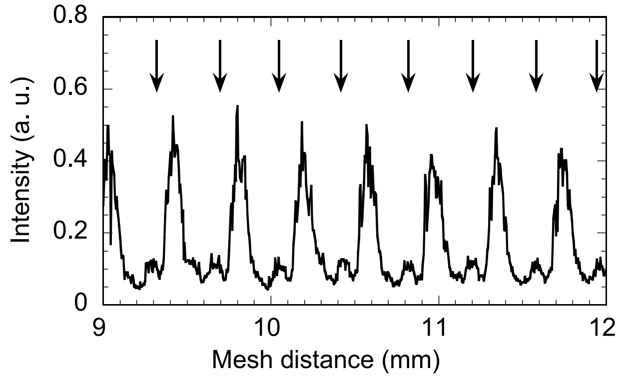

Fig. 4 Fabry-Perot interferometer signal for a case of mode competition.

388.9 GHz was almost equal to the resonance frequency f_c of the $TE_{17,2}$ mode. The total oscillation efficiency was 15%. Figure 3 plots these new power records for gyrotron SH oscillation in the sub-terahertz region. Previous power records [8, 13] are also shown in this figure. Thus, we have succeeded in attaining single-mode oscillation of SH modes at power levels reaching 100 kW.

However, power saturation occurred again. The output power for I_b = 12 A was less than 83 kW. In addition, mode competition resulted from fine adjustments of R_b with small changes in magnetic field strengths at the cavity or at the electron gun. An example of such a case is presented in Fig. 4, which shows the intensity transmitted through a Fabry-Pelot interferometer. A small pulse train indicated by the arrows appears between each main peak corresponding to the $TE_{17,2}$ mode. The presence of the small pulse train indicates simultaneous oscillation of the neighboring SH $TE_{8,5}$ mode. The combination of simultaneously oscillating modes changes as a function of the operation conditions. For example, for V_k greater than 60 kV, we observed simultaneous oscillation of the FH $TE_{4,3}$ mode. In gyrotron physics, it is very interesting to study SH mode oscillation as the dominant mode with mode competition from a FH mode [14], and a detailed study of these phenomena will be subject of a future presentation.

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