

Observation of Simultaneous Oscillation of Multiple Modes in a CW 300 GHz Gyrotron

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Multi-mode oscillation was observed in a 300 GHz fully CW gyrotron. It has been developed and installed in the Research Center for Development of Far-Infrared Region, University of Fukui as a power source of a submillimeter-wave material processing system. This gyrotron delivers 1.75 kW/CW at maximum. The radiation pattern is a Gaussian beam when the magnetic field strength B_c at the cavity is properly adjusted. However, within a range of B_c values, simultaneous oscillation of competing modes is observed, manifesting in radiation of the output power in multiple directions.

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Medium-power millimeter/submillimeter waves have numerous applications in various fields. Among those applications, ceramic sintering and material processing are most promising. Recently, since a strong non-thermal effect is expected for higher frequency power, use of 20 - 30 GHz gyrotrons has become popular [1]. A CW gyrotron with a frequency of hundreds of GHz has not yet been realized as a power source for practical applications, even though a stronger non-thermal effect can be expected. Thus, realization of a gyrotron with this frequency range and kW order power is strongly desired.

Mode competition is a serious problem in the design and operation of a medium to high power, high frequency gyrotron because the mode density inevitably becomes very high owing to the extremely oversized cavity. Usually, the designated mode with the smallest starting current grows by suppressing competing modes until finally, single-mode oscillation is realized.

However, there is a chance of multi-mode oscillation depending on the operation condition. We have observed this phenomenon on a fully CW 300 GHz gyrotron called FU CW I. This is very interesting from the viewpoint of the gyrotron physics. Moreover, understanding of multi-mode oscillation is a basis for the development of medium-power CW gyrotrons with further higher frequencies.

This gyrotron with kW order output power has been developed according to the above requirements and installed in the Research Center for Development of Far-Infrared Region, University of Fukui. It is the first gyrotron having these parameters for practical applications [2]. FU CW I works at the fundamental electron cyclotron resonance in a 12 T liquid helium-free superconducting magnet. It is operated at a relatively low cathode voltage of

15 kV. The maximum beam current is 1 A.

The designated cavity mode of FU CW I is $TE_{22,8}$. The radius of the flat region of the cavity R_c is 8.39 mm, and the resonance frequency of the $TE_{22,8}$ mode is almost 300 GHz. The length of the flat region of the cavity is 15 mm and the total Q value including the Ohmic loss is about 6000 [3]. The gyrotron is equipped with a mode converter composed of a Vlasov-type radiator and three beam-shaping mirrors. The output power is delivered through the vacuum window in a Gaussian beam. The vacuum window is made of BN and its diameter is 80 mm. This gyrotron can be operated in either CW mode or pulse mode.

A performance test of FU CW I has been carried out in advance of its commissioning in a material processing system. A maximum CW output power of 1.75 kW was attained. This power was measured with a water load attached directly to the vacuum window. The radiation pattern was measured with an infrared camera. A Gaussian beam with a very low-level side lobe was confirmed when the magnetic field strength B_c at the cavity was properly adjusted. The oscillation was identified as the designated $TE_{22,8}$ mode from frequency measurements performed by a combination of a harmonic mixer and a local oscillator [4].

Mode competition was observed in the range of the parameter space of B_c and the cathode voltage V_c . Several modes oscillated simultaneously. This manifested in radiation of the output power into multi directions. Then the radiation pattern was measured in detail. A 1-mm-thick polyvinyl chloride plate was used as an absorber. Because of very low thermal conductivity of polyvinyl chloride, thermal diffusion was negligible in a few tens of seconds necessary for the temperature measurement. Therefore, the profile of temperature rise was considered to well represent the radiation pattern.

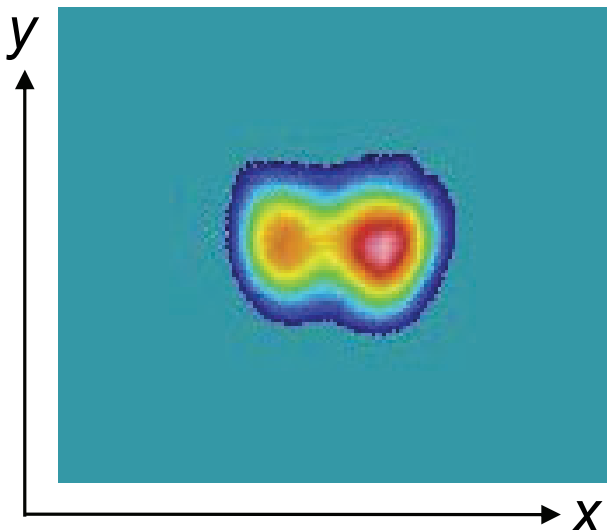


Fig. 1 An example of the infrared camera image for $V_c = 15$ kV and $B_c = 10.90$ T. The distance between the two peaks is about 3 cm.

Figure 1 represents a typical temperature profile for the case of two peaks. In this case, V_c was 15 kV and the beam current I_b was about 1 A. The multi-peak radiation pattern depends sensitively on B_c and V_c . For $V_c \leq 12$ kV, single-peak radiation is observed within almost all ranges of B_c .

The multi-peak character also depends on B_c . Figure 2 shows the temperature distribution of the absorber along the horizontal direction (along the x direction of Fig. 1) for different B_c values, with V_c fixed at 15 kV. Multi peaks always appear along the horizontal direction, and the position corresponding to each peak does not vary for different values of B_c . Therefore, each peak is considered to correspond to a different oscillation mode. As shown by the red line in Fig. 2, only one beam is radiated when B_c is set at 10.95 T. This beam is radiated in the same direction as that for V_c of 12 kV, for which only one beam is radiated within a wide range of B_c values. This oscillation was identified as the $TE_{22,8}$ mode from the frequency measurement. Thus, the radiation shown by the red line in Fig. 2 originates from the $TE_{22,8}$ mode. We refer to this beam as Beam 1.

The peak temperature of the absorber corresponding to the power of Beam 1 decreased with decreasing B_c . A new peak appeared in the position left of the Beam 1 peak when B_c was slightly decreased, as depicted by the black line in Fig. 2. We call it Beam 2. The output power of the oscillation corresponding to this peak was rather low and disappeared for smaller B_c values. Instead, another peak turned up in between Beam 1 and Beam 2. The green line in Fig. 2 represents this case. This peak is called Beam 3. When B_c was further decreased, Beam 1 disappeared and Beam 3 alone was observed as shown by the blue line in Fig. 2. The difference in B_c between the case of the red line

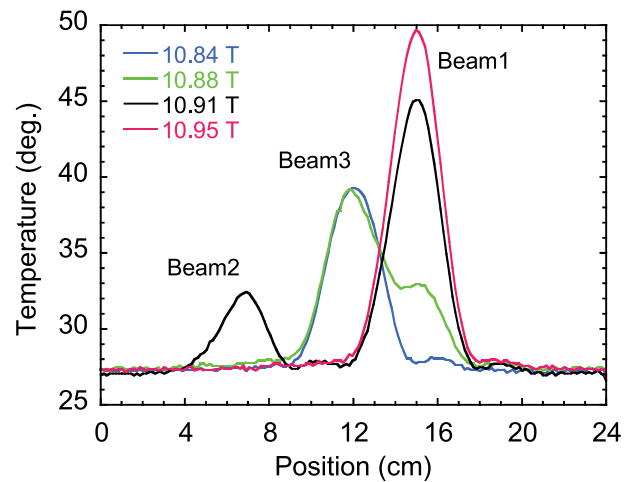


Fig. 2 Temperature distributions along the horizontal line that passes the peak temperature position.

and the case of the blue line was 0.11 T.

In addition to the $TE_{22,8}$ mode, a $TE_{19,9}$ mode was also identified from the frequency measurement. The difference of 0.11 T in B_c just corresponds to that between the optimum values of B_c for both modes. Therefore, Beam 3 is considered to originate from the $TE_{19,9}$ mode. The counter-rotating $TE_{19,9}$ mode is the most dangerous competing mode. The oscillation mode corresponding to Beam 2 has not been identified yet.

The $TE_{22,8}$ mode and the $TE_{19,9}$ mode simultaneously oscillate in a range of B_c values when V_c is larger than 13 kV. When the beam current I_b is decreased, the oscillation range of B_c becomes slightly narrower for each mode. Finally, the multi-oscillation region disappears for I_b smaller than 0.3 A.

The radiation pattern was measured in the pulse mode to avoid burn-up of the absorber, but the infrared camera recorded the temperature profile on the absorber plate as a result of time integration of the absorbed power. Therefore, the multi-peak pattern does not directly indicate simultaneous oscillation of the multi modes. For this reason, pyroelectric detectors were set on the lines of Beam 1 and 3. The signals of the two detectors clearly showed simultaneous and full-time oscillation of the two modes during the cathode voltage pulse. For each beam, the dependence of the signal intensity on B_c is similar to the dependence of the temperature rise on B_c .

Simultaneous oscillation of multi modes was observed in a 140 GHz gyrotron [5]. The main operation mode of this gyrotron was relatively low-mode TE_{03} at the fundamental resonance. Competition between the fundamental and the second harmonic oscillations was also reported [6]. The frequency of the second harmonic oscillation was 383 GHz. Compared with these experiments, the oscillation modes of FU CW I are very high.

Another problem is how the counter-rotating mode

can be radiated as a Gaussian beam through the internal mode converter of the Vlasov type. The co-rotating $TE_{19,9}$ mode could be excited, but the optimum radius of the electron beam is considerably smaller than that of the counter-rotating $TE_{19,9}$ mode. We have not come to the physical understanding of this phenomenon yet. Results of more detailed analysis of experimental data and theoretical discussion will be published elsewhere.

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