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Evaluation of Electron Beam Properties in Sub-THz Gyrotron Experiments
サブテラヘルツ帯ジャイロトロン実験における電子ビーム特性の評価

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A high performance triode magnetron-injection gun (MIG), which generates a laminar electron beam with very small velocity spread, was designed, constructed and tested in a 300 GHz gyrotron. To investigate the electron beam quality, the oscillation characteristics associated with the electron beam properties were compared with the numerical characteristics. The calculation results provided a reasonable explanation for the observed behaviours of the power variation for the electron beam parameters. It was confirmed that the MIG provides the expected beam properties in a wide range of operating window.

1. Introduction

Gyrotrons are known as a promising radiation source to cover the power-gaps in a frequency range from 0.1 to several THz. Up to now, megawatt-class CW tubes at frequencies from 28 to 170 GHz have been developed and applied to nuclear fusion experiments. For advanced plasma diagnostics, and electron heating in the future devices such as IGNITOR and DEMO, 200-300 GHz high-power tubes will be required. We have been developing a 300 GHz tube, which is applicable to collective Thomson scattering (CTS) diagnostics in the large helical device (LHD).

In this frequency range, avoiding mode competition is critical to realizing high-power and stable oscillation. A moderately over-moded cavity was employed to ensure sufficient isolation of a desired mode from neighbouring modes, and to achieve high power output simultaneously. In this case, however, the magnetron-injection gun (MIG) should be operated in a severe condition, in which the electron beam is strongly influenced by the space-charge effect.

A high performance triode MIG, which provides a laminar electron beam with very small velocity spread, was designed [1] and tested in a prototype tube [2]. To evaluate the quality of electron beam, calculated oscillation characteristics were compared with observed ones. Here, the electron trajectories were simulated using a computer code EGUN [3]. The interaction between the beam and waves in the cavity was calculated with a mode-competition code [4] for various operating conditions. The calculation results provided a reasonable explanation for the observed behaviours of the power variation for the electron beam parameters.

2. Experimental Setup

A conventional cylindrical cavity with linear tapering on both sides was designed with the transverse electric mode of co-$TE_{14,2}$, where “co-“ denotes the co-rotation with respect to the electron gyration. Figure 1 shows the cavity profile, the straight section of which has a radius of 3.405 mm and length of 9.00 mm. Maximum power greater than 200 kW was expected with a beam voltage V_K of -65 kV and current I_B of 10 A. Here, the velocity pitch factor α (≡ $v_\perp/v_{//}$) in the cavity

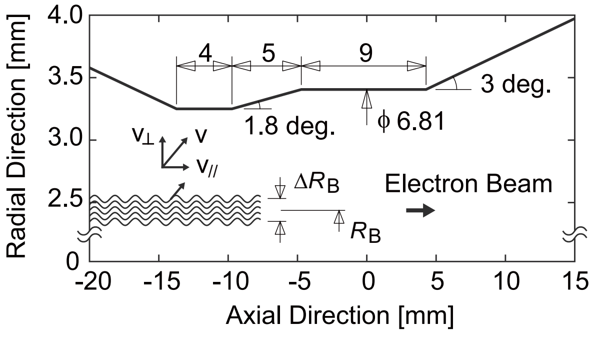

Fig. 1. Cavity profile and a schematic of injected helical electron beams.

is assumed to be α = 1.2. The optimum beam radius, R_B, is 2.42 mm in the cavity.

4. Comparison of experimental and numerical results

We measured the output power while varying the electron-gun-coil current, I_G, which changes the compression ratio of the magnetic fields between the cathode and cavity. The values of V_K, V_{KA} (voltage between the cathode and anode) and I_B were maintained at −60 kV, 24 kV and 10 A, respectively. As the result, not only R_B but also α varies when I_G changes. In the experiments, magnetic field in the cavity was optimized to find a maximum power at each I_G value. The obtained maximum power is shown with circles as a function of R_B in figure 2 (a).

The observed result was compared with the calculated result for the electron beam parameters used in the experiments. Here, α and its spread Δα ($\equiv[\alpha_{max.}-\alpha_{min.}]/\alpha_{average}$) were estimated with EGUN, and plotted as functions of R_B in figure 2 (b). The increase in I_G lowers the beam compression ratio, which leads to an increase in R_B and decrease in α at the same time. The velocity spread was found to be negligibly small. The powers given with some curves in figure 2 (a) were numerically estimated using the above estimated α. In the calculations, the competition with neighbouring modes was also considered. Presently, the effects of spread in the velocity and spread in the radial thickness of the electron beam are not considered in our mode competition code.

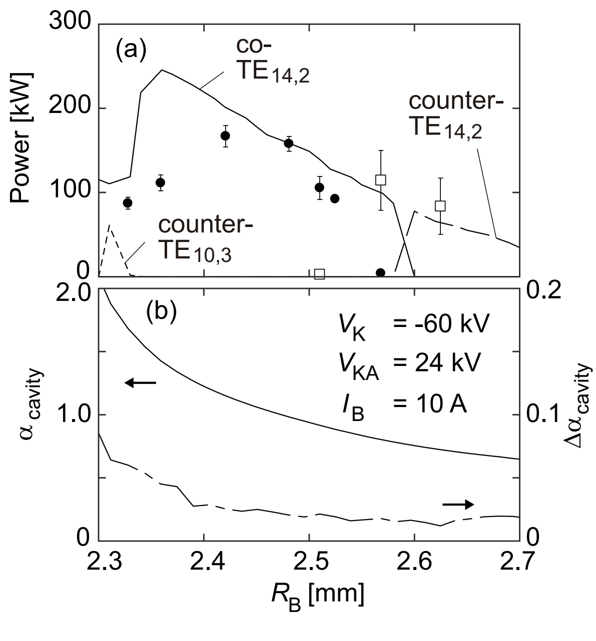

Fig. 2. (a) Calculated (curves) and observed (symbols) powers plotted versus R_B. (b) Values of α and Δα are calculated with EGUN for the parameters used in the experiments.

The calculation result shows the counter-$TE_{10,3}$ and counter-$TE_{14,2}$ can be excited in addition to the co-$TE_{14,2}$ in the R_B region shown in figure 2 (a). The calculated powers for the co-$TE_{14,2}$ mode (illustrated with a solid curve in figure 2(a)) generally reproduce the observed powers. The power has weak dependence on the coupling coefficient in this R_B region. As R_B decreases from 2.42 mm, the calculated power increases with α. Then, however, the power saturates and begins to decrease with R_B, because the excessive α results in over-interaction with the waves. Further reduction in R_B causes competition with the counter-$TE_{10,3}$ mode, which is indicated with a short-dash curve. In contrast, in the region of R_B from 2.42 to ~2.57 mm, the decrease in the power is mainly due to the reduction in α. A further increase in R_B triggers the competition with the counter-$TE_{14,2}$ mode as indicated with the long-dash curve.

Since the mode convertor is prepared only for the co-$TE_{14,2}$ mode in a specified direction of the magnetic fields, the counter-rotating mode is not properly output. To confirm the appearance of the counter-$TE_{14,2}$ mode, the power was measured with the polarization of the magnetic fields reversed. The measured powers for the counter-$TE_{14,2}$ mode are represented by squares in figure 15(a). The transition from co- to counter-$TE_{14,2}$ modes, and its power variation was confirmed as predicted by the calculations.

4. Conclusion

The calculation results provide a reasonable explanation for the observed behaviours of not only the power variation for R_B but also the transition from co-rotating to counter-rotating modes. The important point here is that these results are never obtained without taking into account the electron beam properties predicted by EGUN. This is considered as evidence for the MIG having the designed characteristics.

References

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