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Code Development for the Calculations of the Multifrequency Oscillations and Startup in the Cavity of the Future High-Power Gyrotrons
マルチ周波数発振ジャイロトロンのための計算コード開発

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High-power millimeter-wave gyrotrons are designed for fusion plasma applications. It becomes an indispensable tool for electron cyclotron heating (ECH) in magnetic confinement systems. Recently, many studies have devoted to high-power and long-pulse gyrotrons. In addition, multi-frequency gyrotrons are required for research collaborations. These gyrotrons operate in high-order modes in the resonators and the effective mode density is very high; consequently parasitic modes can be excited. For the gyrotron development in the future plan, the computing code for the excitation of parasitic modes and mode interactions in the resonator has been developed.

1. Introduction

An electron cyclotron heating and current drive is a promising method for controlling plasma pressure and current, their profiles, transport, and magnetohydrodynamics. So it has a high potential for present and future fusion devices [1,2].

Recently, many studies [3,4] have focused on the development of high-power, long-pulse gyrotrons. There is also great interest in multi-frequency gyrotrons for research collaborations. These gyrotrons utilize high-order modes in the resonator and the effective mode density is very high; consequently parasitic modes can be excited. To aid with the development of future gyrotrons, we have performed computer modeling of such parasitic-mode excitation and mode interactions.

Several studies [1,2] have shown that the efficiency of the gyrotron oscillator can be significantly enhanced by optimum design of the cavity. The design of the resonant cavity for gyrotron oscillators requires the knowledge of the RF field profile, resonator eigenfrequencies, mode competitions and the diffractive quality factor. The present code calculates the cavity RF profile function by solving the set of the relativistic single-particle equations of motion and wave equations simultaneously to reach a self-consistent solution in the dynamic system that takes into account the effects of the electron beam in the field produced by a superposition of modes. The power transfer from the electron beam to each individual mode is considered and the possible steady states are determined.

2. Model

To design a gyrotron, it is necessary to numerically solve the equation of electron motion and the wave equation in the cavity, and compute the energy loss or gain. [5,6] Cylindrical polar coordinates are employed due to the cylindrical symmetry of the open-ended cavity. The annular electron beam is generated from the electron gun and beam–wave interactions occur mainly in the uniform middle section of the cavity. We choose the beam radius such that the beam-field coupling is maximized.

The RF profiles must satisfy the radiation boundary conditions at the ends of the cavity. The

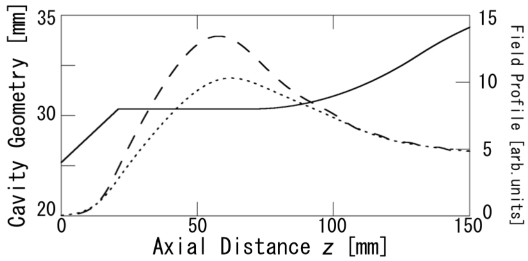

Fig. 1. Cylindrical cavity structures and calculated field profiles as a function of axial distance for the cavity for the 28-GHz, 1-MW gyrotron. The solid curve represents the gyrotron cavity radius, the dashed curve represents the TE_{94} field profile and the dotted curve represents the TE_{83} field profile.

derivative of the profile at the input is given by the initial conditions, and the profile has the form of a traveling wave at the cavity output. The RF field profiles are determined by the beam currents and the coupled equations plus boundary conditions cannot be satisfied for arbitrary initial values of the profile. For this reason, the most efficient method is to solve the coupled equations simultaneously, and vary the value of the operating frequency and the initial profile until the reflection coefficient [6] is minimized. The parallel algorithms [5] are used for the required accuracy in calculation and the reduction of the computer time.

3. Results

Our calculations were carried out for the gyrotron configuration in the GAMMA 10 tandem mirror, which uses an 80 kV, TE_{83}-mode cavity designed to operate at 28 GHz [7].

Figure 1 shows the dependence of the cavity radius and calculated field profile as a function of axial position in the cavity for the 28 GHz TE_{83} mode and the 35 GHz TE_{94} mode. By changing the

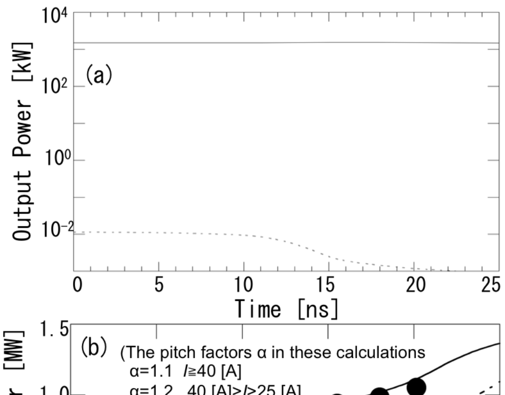

Fig. 2. (a) Time dependence of output power in various modes for the beam currents I=40 A, the pitch factor a=1.1. The TE_{94} mode is shown by the solid lines and the TE_{93} parasitic modes are shown by the dotted lines.
(b) Beam current dependence of experimental and calculated output power for the gyrotron. The circles and squares represent experimental data and the curves represent calculated output powers. The data for the TE_{83} mode are shown by the filled circles and the solid curve. The data for the TE_{94} mode are shown by the filled squares and the dashed curves.

external magnetic field, the different modes can be induced at different frequencies with a similar efficiency. From these calculations, the reflection coefficient is less than 0.01 and the total efficiency of each mode is about 40%.

One of the most important problems in the design of gyrotrons is to ensure that the device operates in the desire mode. Figure 2(a) shows example calculation results for competition between the TE_{94} operating mode and a neighboring mode. The parasitic TE_{93} mode oscillates with a very small amplitude and output power and It was found that if the operating mode of the gyrotron is oscillating, it can suppress neighboring modes.

Figure 2(b) shows a comparison between the calculated and experimental results. The circles and squares represent the experimental output power and the curves represent the calculated values. The results for the TE_{83} mode at 28 GHz and for the TE_{94} mode at 35 GHz are shown in this figure. The calculation results are adjusted so that the calculated window output power is given by the product of the calculated cavity oscillation power with the relevant pitch factor in the range 1.1–1.3 and the calculated transmission efficiency [7]. The difference between the calculated and experimental results is found to be less than 10%.

Considering the need for collaborative research with regard to gyrotron development, an experimental and design study of multi-frequency power gyrotrons has been undertaken. We will continue in our attempts to develop gyrotrons that can operate in the wide frequency range from 14 to 300 GHz for present and future devices up to DEMO.

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