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Design for Power Enhancement of a Gyrotron for Practical Use in Collective Thomson Scattering Diagnostic in LHD

LHDにおける協同トムソン散乱計測用 300 GHz帯実機ジャイロトロンの高出力化設計

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A high power pulsed gyrotron is under development in FIR-UF for application to 300 GHz band Collective Thomson Scattering (CTS) diagnostics in the Large Helical Device (LHD). Single-mode operation with 246 kW maximum output power at 295 GHz was demonstrated with a prototype gyrotron. Based on these results, we designed a new gyrotron for use in LHD experiments that require high power probe waves greater than 300 kW.

1. Introduction

As research for nuclear fusion progresses, it is important to understand the behavior of high-energy ions in order to confine these ions stably in burning plasmas. Collective Thomson Scattering (CTS) diagnostics is a promising method for evaluating the velocity distribution function of these high energy ions.

At present, a 77 GHz gyrotron for electron cyclotron heating is used as a CTS wave source in the Large Helical Device (LHD) [1]. However, the low frequency probe wave suffers from refraction, cut-off and absorption at the electron cyclotron resonance layer. Additionally, signal detection is severely affected by background noise from electron cyclotron emission. Avoidance of these problems requires a 300 ~ 400 GHz gyrotron with more than several hundred kilowatts.

In FIR-UF, gyrotrons have been previously developed for CTS diagnostics of the LHD. First, we developed a 400 GHz band second harmonic gyrotron. We successfully generated high power single mode oscillation of a second harmonic mode [2], and realized a maximum power approaching 100 kW at 389 GHz [3]. However, mode competition with a fundamental harmonic mode prevented attainment of higher power [4]. Thus, we have started to develop a gyrotron with a 300 GHz band fundamental harmonic, a frequency suitable for the LHD experiments. A prototype gyrotron has demonstrated an oscillation at over 200 kW [5]. In this paper, we present results from the prototype tube, and the design of a new gyrotron tube for diagnostic use in the LHD.

2. Results from Prototype Gyrotron

2.1 *Design concept*

The prototype gyrotron tube was designed to demonstrate single mode oscillation at 300 GHz with more than several hundred kilowatts of power at the fundamental harmonic. A liquid He-free 12 T super conducting magnet (SCM) with 100 mm bore at room temperature was used in this research. Generally, a higher power gyrotron requires a higher order oscillation mode in order to decrease the heat load on the cavity surface. However, when a higher order mode is selected the cavity diameter increases, and the 100 mm bore SCM becomes unusable. However, a gyrotron for CTS diagnostics can reduce the cavity heat load with a finite duty cycle, by around 10%. Therefore, we can select a moderately high order mode as the operating mode. For the prototype tube we selected the $TE_{14,2}$ mode because it is well isolated from neighboring modes. Hence it should demonstrate successful mode competition, and a stable and single mode oscillation is expected.

2.2 *Experimental results*

The prototype gyrotron tube was equipped with an internal mode converter. We observed a stable, single mode oscillation with the $TE_{14,2}$ mode and 293.981 GHz narrow-band frequency spectrum. The measured radiation pattern was similar to the calculated pattern, and a Gaussian-like wave beam was confirmed. The oscillation power increased with cathode voltage V_K and beam current I_B (Figure 1), with a maximum output power of 246 kW at V_K = 65 kV and I_B = 14 A. The efficiency was higher than 30% in the low I_B region and gradually decreased with I_B, but still remained higher than 25%. From these results, the design concept was verified.

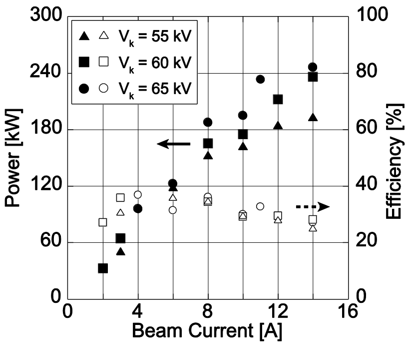

Fig.1. Measured power and efficiency

3. Design of New Tube

3.1 *Selection of oscillation mode*

Based on the results from the prototype tube, we targeted greater than 300 kW oscillation for the new tube. Therefore, an oscillation mode with a higher order than the $TE_{14,2}$ mode was required to reduce the heat load on the cavity surface. After exploring various modes, the $TE_{22,2}$ mode was selected as the operating mode. The oscillation power for V_K = 65 kV, I_B = 15 A and pitch factor α = 1.2, calculated with a mode competition code as a function of the magnetic field strength (Figure 2), predict a stable and single mode oscillation for the $TE_{22,2}$ mode.

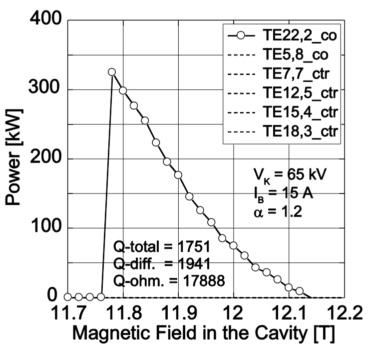

Fig.2. Calculated power of the $TE_{22,2}$ mode

During the design process, we discovered an interesting competition between fundamental modes. Two mode competition calculations, including the promising $TE_{18,2}$ mode, are shown in Fig. 3. Figure 3(a) depicts interaction of the $TE_{18,2}$ mode with a lower field $TE_{11,4}$ side mode. However, inclusion of a further lower field $TE_{17,2}$ mode drastically changed the calculation result (Fig. 3 (b)). The $TE_{11,4}$ mode was suppressed by the $TE_{17,2}$ mode, suggesting a chain of mode competition, and consequently single mode oscillation of the $TE_{18,2}$ mode was realized. However, the $TE_{18,2}$ mode brings a risk of mode competition (Fig. 3 (a)) and therefore the $TE_{18,2}$ mode was not selected as the oscillation mode.

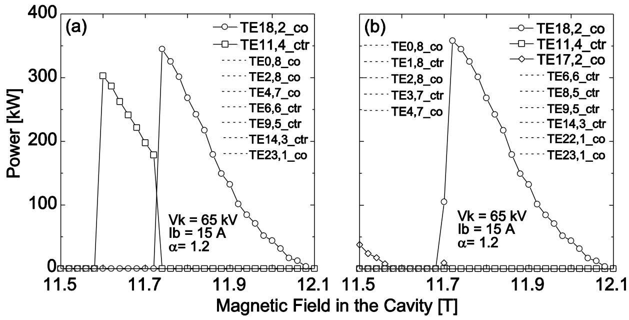

Fig.3. Result of mode competition calculation. Fig. (a) includes $TE_{18,2}$, $TE_{11,4}$ and other near modes. Fig. (b) includes $TE_{18,2}$, $TE_{11,4}$, $TE_{17,2}$ and other near modes.

3.2 *Electron gun design*

Based on these results, a new electron gun was designed for the gyrotron tube. A plot of the pitch factor in the cavity α_{cavity} and spread of the pitch factor $\Delta\alpha_{cavity}$ as functions of I_B and cathode-anode voltage V_{KA} (Figure 4) show that α_{cavity} is widely adjustable, and $\Delta\alpha_{cavity}$ decreases below 5% in the region α = 1.0 ~ 1.3.

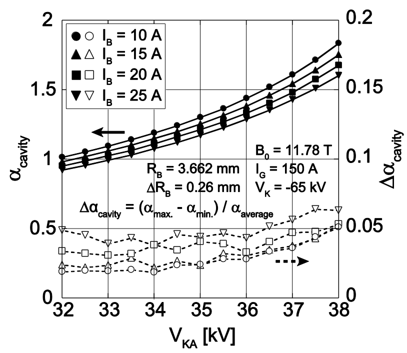

Fig.4. Plots of α_{cavity} and $\Delta\alpha_{cavity}$ as functions of I_B and V_{KA}

Oscillation tests of this gyrotron will begin in April, 2015.

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