Subterahertz gyrotron developments for collective Thomson scattering in LHD

Subterahertz gyrotron developments for collective Thomson scattering in LHD[a)]

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Collective Thomson scattering (CTS) is expected to provide the spatially resolved velocity distribution functions of not only thermal and tail ions but also alpha particles resulting from fusion reactions. CTS using gyrotrons with frequency higher than the conventional ones used for plasma heating would have advantages to alleviate refraction, cutoff effects, and background electron cyclotron emission noise. Therefore, a high-power pulse gyrotron operating at approximately 400 GHz is being developed for CTS in Large Helical Device (LHD). A single-mode oscillation with a frequency greater than 400 GHz, applying the second-harmonic resonance, was successfully demonstrated in the first stage. At the same time, concrete feasibility study based on ray tracing, scattering spectra, and electron cyclotron emission calculations has been conducted. © *2008 American Institute of Physics.* [DOI: 10.1063/1.2966372]

I. INTRODUCTION

Presently, the demand for terahertz radiation sources is on the rapid increase for various applications such as nuclear fusion plasma diagnostics, the solid-state physics research, and sensing and imaging techniques.[1] In particular, high-power radiation sources with a narrow bandwidth in the subterahertz frequency regions are desired for collective Thomson scattering (CTS) to diagnose velocity distribution functions of ions in nuclear fusion plasmas. Gyrotrons could be the most suitable source of the probe beam for CTS diagnostics. In recent years, utility of CTS using conventional gyrotrons has been demonstrated at some Tokamaks. Under the circumstances, development of gyrotron with frequency considerably higher than conventional ones has been initiated in order to measure the ion temperature of high-density plasmas in Large Helical Device (LHD). This paper is organized as follows. First, the explanation of CTS and the advantages of utilizing a high-frequency gyrotron for CTS in terms of accessibility to plasma and reduction of the background electron cyclotron emission (ECE) noise are presented in Sec. II. Next, our plan for the development of a high-frequency gyrotron is briefly described in Sec. III. The results of the first stage experiment using an existing gyrotron and prospects for the next-step gyrotron are discussed in Sec. IV. Finally, this paper is summarized in Sec. V.

II. CTS IN LHD

A criterion for the CTS is given by the well-known Salpeter parameter. Figure 1 shows the calculated results of the Salpeter parameter as a function of scattering angles and frequencies. In the calculation, the electron temperature and density are set to be 1 keV and $1\times10^{20}\ \mathrm{m}^{-3}$, respectively. A 28 THz CO_2 laser can satisfy the conditions required for CTS only at scattering angles of less than 1°, which leads to poor spatial resolution. Therefore, a source with frequency lower than that of CO_2 laser is required for CTS. Conventional gyrotrons, with frequencies of around 100 GHz, used for plasma heating seem to be effective probe beams for CTS because the scattering is collective at all angles. However, the use of such gyrotrons involves many difficulties such as cutoff, refraction, absorption at electron cyclotron resonance, and huge background noise due to ECE including harmonics. Despite the difficulties, CTS using conventional gyrotrons has been applied to measure the fast ion distribution function in JET, FTU, TEXTOR, and ASDEX recently.[2] However, such experiments were conducted in qualified magnetic configurations to avoid strong ECE noise.

On the one hand, superdense core (SDC) plasmas with internal diffusion barrier observed in LHD (Ref. 3) have attracted attention because they may provide a new operational scheme in future fusion reactors. However, in such high-density plasmas, the usual charge exchange recombination spectroscopy is not available to diagnose ion temperature because of pumping out of impurities from plasma and attenuation of probe neutral beams. CTS using not conventional gyrotron but high-frequency one is a possible alternative method to measure the ion temperature in SDC plasmas. Therefore, as a concrete plan, development of a high-frequency gyrotron has been initiated for CTS in LHD. To determine the specifications for the CTS gyrotron, the expected background ECE intensity and power of scattered wave are estimated under the real LHD configuration. In the standard magnetic configuration of LHD, the magnetic axis is located at 3.6 m with a magnetic field strength of 2.75 T. Under the configuration, the background ECE intensity is calculated in order to clarify the most suitable frequency because background ECE is the most serious issue to be solved in CTS utilizing gyrotrons. The relationship between the lo-

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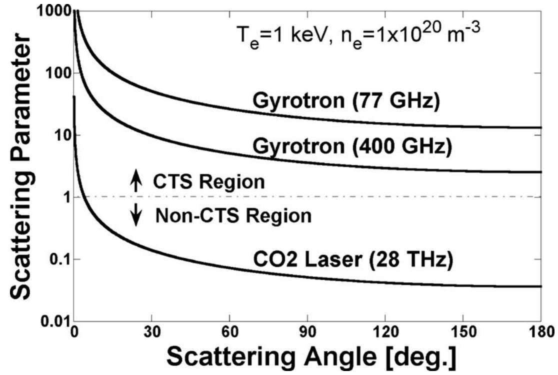

FIG. 1. Salpeter parameter vs frequencies and scattering angles.

cal electron temperature in plasma and equivalent radiation temperature integrated along the line of sight is expressed below using the radiation transfer equation and Kirchhoff's law,[4]

$$T_{\omega,\mathrm{rad}} = \int_0^s T_e(s')\alpha_\omega(s')\exp\left[-\int_{s'}^{s}\alpha_\omega(s'')ds''\right]ds'. \quad (1)$$

Here, α_ω is the absorption coefficient at a frequency ω including influence of harmonic radiations. Figure 2 shows the expected ECE radiation temperature integrated along the line of sight from the 10 O port of LHD as a function of frequency. Here, the central electron density and temperature are 1×10^{20} m^{-3} and 2 keV, respectively, and their profiles are modeled from typical Thomson scattering data. The background ECE noise can be avoided by choosing a frequency around 330 GHz, which corresponds to the valley between the fourth and fifth emissions, or around 400 GHz, which corresponds to the valley between the fifth and sixth emissions, for a probe beam. Therefore, we are now proposing the use of a gyrotron operating at about 400 GHz for the CTS diagnostic in LHD and it is being developed at the Research Center for Development of Far-Infrared Region of University of Fukui.

The required pulse width in the development of gyrotron for CTS is also estimated roughly to achieve a signal to noise (SN) ratio of 5. The power of the scattering wave is calculated under the LHD configuration based on the ray tracing and the following expression:

$$P_S = P_{\mathrm{in}} n_e r_e^2 \Gamma S(k,\omega)\Delta f \lambda_{\mathrm{in}}^2/(\sqrt{\pi}w_0 \sin \theta_S). \quad (2)$$

Here, P_s, P_{in}, n_e, r_e, Γ, S, Δf, λ_{in}, w_0, and θ_s are the scattered power, incident power, electron density, classical electron radius, geometrical factor, scattering spectrum function that has the information of scattered wave spectra, frequency bandwidth, wavelength of incident wave, beam waist size, and scattering angle, respectively. From the calculation results assuming an incident power of 100 kW, geometric factor for O-mode, incident wavelength of 0.749 mm, beam waist size of 30 mm, and scattering angle of 104°, the scattering energy per frequency bandwidth of 100 MHz is expected to be about 10^{-2} eV at around 400 GHz.[5] On the other hand, from the above mentioned ECE calculation shown in Fig. 2, the expected ECE radiation temperature at around 400 GHz is of the same order as the scattering energy. Therefore, when the main noise source is regarded as only background ECE, the necessary pulse width of the gyrotron to assure a SN ratio of 5 can be estimated from the following relationship:[6]

$$S/N = [P_S/(P_S + P_N)]\sqrt{1+\tau\Delta f}. \quad (3)$$

Here, P_N is noise power (i.e., background ECE power) and τ is the pulse width. In the case of a frequency bandwidth of 100 MHz, the required pulse width for a 400 GHz gyrotron is estimated to be 1 μs at minimum. From the viewpoint of improving the SN ratio, prolonging the pulse width is better than increasing the scattering power because the term $P_S/(P_S+P_N)$ can never exceed unity. Therefore, in a practical sense, a longer pulse width will be more desirable since several other factors may degrade the SN ratio. The pulse width of up to 1 ms may be in the attainable zone in the development of a 400 GHz gyrotron with a power of about 100 kW.

III. PLAN FOR DEVELOPMENT OF 400 GHz GYROTRON

Our main aim in the development of a high-power 400 GHz gyrotron in the first stage is to demonstrate single-mode oscillation with a frequency of about 400 GHz. The existing gyrotron is optimized for fundamental TE0,3,1 mode oscillation with a frequency of 203 GHz at 7.7 T, which is nearly the maximum achievable value using the built-in superconducting magnet. Therefore, we have to utilize second-harmonic resonance to produce oscillations at 400 GHz. Based on the experimental results, the next-step gyrotron, which should be optimized for 400 GHz oscillation, will be designed. The advantage of using second-harmonic operation is that the magnetic field can be reduced by a factor of 2, which can reduce the cost of development. The most difficult aspect of achieving single-mode oscillation at second-harmonic resonance is mode competition. In general, the starting currents for second harmonics are higher than those of the fundamental modes. As a result, the fundamental mode is excited primarily and the oscillation of the second-harmonic modes will be suppressed. Moreover, the mode density for second-harmonic modes is much higher than that for fundamental modes. Therefore, generating single-mode oscillations at the second harmonic is difficult and challenging. However, the risk of mode competition will be suppressed to some extent by diminishing the cavity radius. The cavity radius of the existing gyrotron is 2.39 mm, which is about one-tenth that for conventional gyrotrons used for

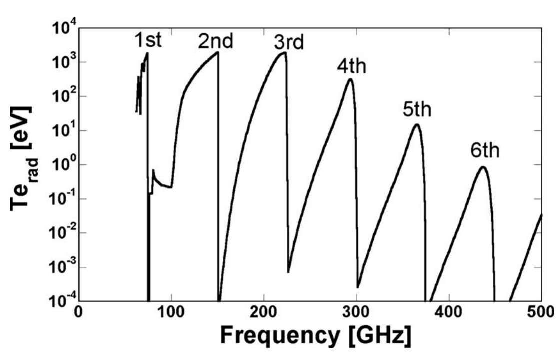

FIG. 2. Expected background ECE spectrum in LHD.

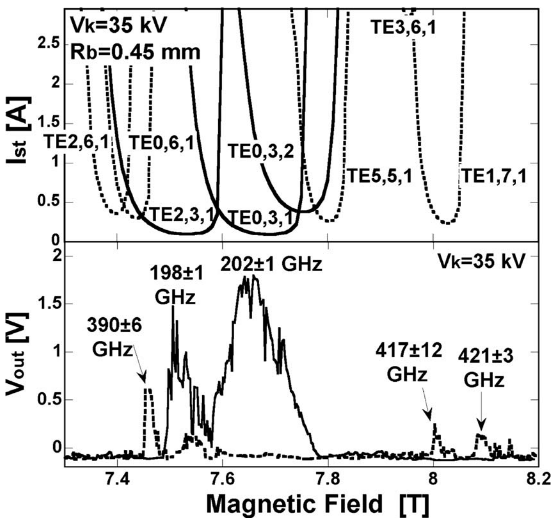

FIG. 3. Comparison of oscillations between calculation and experiment.

plasma heating because the short-pulse gyrotron does not have a strong constraint for allowable heat loss in the cavity. Thus, single-mode oscillations at the second harmonic without mode competition are expected in the existing gyrotron.

IV. EXPERIMENTAL RESULTS

Using the existing gyrotron, the dependence of oscillation on the magnetic field at the cavity was studied, and the results are shown in the lower portion of Fig. 3. In the experiment, the typical pulse width, collector current, and cathode voltage are 4 μs, 1 A, and 35 kV, respectively. Starting currents are also given in the upper portion of Fig. 3. In the figure, the solid and dashed lines correspond to the fundamental and second-harmonic modes, respectively. In the experiment, fundamental mode oscillations are detected using an attenuator in order to protect the diode detector during magnetic field scan. Therefore, oscillations for the second-harmonic modes are not detected in this case because the output power of second-harmonic modes is much less than that of fundamental modes. Two strong oscillations are identified as the fundamental TE2,3,1 and TE0,3,1 modes judging from oscillating magnetic field regions and oscillation frequencies measured using a Fabry–Pérot interferometer. These experimentally observed frequencies accord well with the resonance frequencies of the TE2,3,1 and TE0,3,1 modes at the cavity. Then, for detecting second-harmonic oscillations, a high-pass filter with a cutoff frequency of 293 GHz was inserted in front of the detector. Several second-harmonic oscillations with frequencies of about 400 GHz were observed successfully. For example, the oscillation mode at 8.1 T is expected to be TE 1,7,1. Disagreement of the oscillating magnetic field region between experiment and calculation may result from slight errors in setting the magnetic field and in manufacturing the cavity. The fact that single-mode oscillation with a frequency of around 400 GHz at the second harmonic is successfully demonstrated encourages us to develop the next high-power second-harmonic gyrotron. On the other hand, it should be noted that second-harmonic TE5,5,1 mode oscillation was not observed experimentally. One of the conceivable reasons is mode competition with the axial higher-order mode of the fundamental TE0,3,1 mode, i.e., the TE0,3,2 mode. In general, the starting current for the axial higher-order mode with axial mode number p is about p^2 times larger than that for the axial fundamental mode because the diffractive Q is inversely proportional to the square of p. As a result, axial higher-order modes become, in general, difficult to oscillate. However, since the Q value of our gyrotron is much larger than those of conventional gyrotrons developed for plasma heating, the axial second mode may oscillate easily. Therefore, from the experimental results of the existing gyrotron, the second-harmonic mode, whose oscillation region is located at a magnetic field strength just above that of a fundamental oscillation mode (just like TE5,5,1), is not suitable for the design mode of a second-harmonic gyrotron because there is high risk of it being suppressed by mode competition from the powerful fundamental mode.

Based on the experimental results, the optimum mode for a high-power second-harmonic gyrotron as a next step has been explored, and the TE6,5,1 mode has been selected for the new cavity radius of 2.99 mm. To increase the output power, the electron gun and power supply system are also improved. Testing of this new gyrotron has just begun.

V. SUMMARY

The merits of using a high-frequency gyrotron instead of a conventional gyrotron for CTS in LHD have been discussed from the viewpoints of achieving high SN ratio and sufficient scattering angles simultaneously. In order to develop a high-frequency gyrotron with a frequency of around 400 GHz, the oscillation characteristics at around 400 GHz utilizing the second-harmonic resonance were studied using an existing gyrotron. Furthermore, a new gyrotron optimized for second-harmonic oscillation at high-power levels has been designed.

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