Development of 300 GHz Band Gyrotron for Collective Thomson Scattering Diagnostics in the Large Helical Device[*)]

Teruo SAITO, Yuusuke YAMAGUCHI, Yoshinori TATEMATSU, Masafumi FUKUNARI, Takumi HIROBE, Shunsuke TANAKA, Ryuji SHINBAYASHI, Takashi SHIMOZUMA[1)], Shin KUBO[1)], Kenji TANAKA[1)] and Masaki NISHIURA[2)]

Research Center for Development of Far-Infrared Region, University of Fukui, Fukui 910-8507, Japan
[1)]*National Institute for Fusion Science, Toki 509-5292, Japan*
[2)]*Graduate School of Frontier Sciences, The University of Tokyo, Kashiwanoha 277-8561, Japan*

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A 300 GHz pulse gyrotron has been developed for use in collective Thomson scattering (CTS) diagnostics in the Large Helical Device (LHD). Single-mode oscillation power of more than 320 kW was produced. The radiation beam has a Gaussian pattern. The frequency spectrum is very narrow and stable across the pulse width. No competing mode was observed in the oscillation pulse, including during the turn-on and turn-off phases.

Keywords: gyrotron, sub-THz, collective Thomson scattering, LHD

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Collective Thomson scattering (CTS) diagnostics using gyrotrons that operate at around 100 GHz for electron heating have been developed [1, 2]. Sub-THz waves are appropriate as power sources because they are almost free from both refraction and/or absorption in plasmas and strong electron cyclotron emissions (ECEs). The probe's wave power should be more than 100 kW to realize a suitable signal-to-noise (SN) ratio [3]. We have thus developed a high power sub-THz gyrotron for use in CTS diagnostics in the Large Helical Device (LHD).

The initially developed second harmonic gyrotron demonstrated single mode oscillation that approached 100 kW at 389 GHz. However, a competing fundamental harmonic mode prevented further power enhancements [4]. We subsequently developed a fundamental harmonic prototype gyrotron and used it to verify the design concept for stable single-mode oscillation [5]. Use of the same design concept to produce a whispering gallery mode (WGM) has allowed a gyrotron to be designed and fabricated for use in CTS diagnostics in the LHD.

The sub-THz gyrotron for CTS is operated in pulse mode. The designed operating frequency is 303.3 GHz, which corresponds to the minimum for the ECE for standard LHD operation. A moderately high order mode is used to satisfy requirements for mode competition avoidance and low cavity surface ohmic loss simultaneously. The oscillation mode is the $\mathrm{TE}_{22,2}$ mode, which is a WGM similar to the $\mathrm{TE}_{14,2}$ mode used in the prototype gyrotron. The mode number was increased to extend the pulse width and the duty ratio by up to 10%.

WGM modes were used in the initial development stage for gyrotrons for fusion plasma heating because they oscillate stably without mode competition [6, 7]. Volume modes were then used to reduce the ohmic loss for the continuous wave (cw) 1 MW oscillation required for the International Thermonuclear Experimental Reactor (ITER) gyrotron [8]. Because cw oscillation is not required for the CTS power source, WGM modes are promising for complete suppression of spurious modes, including oscillation pulse turn-on and turn-off phases.

Design calculations were performed to assess the dependence of the oscillation power and its efficiency on beam current. Oscillation power of more than 300 kW was expected for a beam voltage V_k of 65 kV, a beam current I_B of 15 A, and a velocity pitch factor α of 1.2. While cavity length was optimized for this parameter set, higher powers were expected for larger I_B. An electron gun was designed and optimized for the $\mathrm{TE}_{22,2}$ mode using the design principle reported in [9]. High-quality electron beams with appropriate α values and small velocity spreads can be generated for I_B up to 20 A [10].

The gyrotron is mounted on a liquid He-free 12 T superconducting (SC) magnet. The room temperature bore diameter is 100 mm. An internal mode converter composed of a helical-cut Vlasov-type launcher and four mirrors is installed in a rather narrow room.

Oscillation tests have been carried out at high power. Figure 1 shows the high power oscillation test results in addition to previously reported data [10]. Specifically, a new maximum power of more than 320 kW was achieved [11]. The beam voltage was 65 kV, while other parameters such as the anode voltage were optimized for each beam cur-

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author's e-mail: saitot@fir.u-fukui.ac.jp

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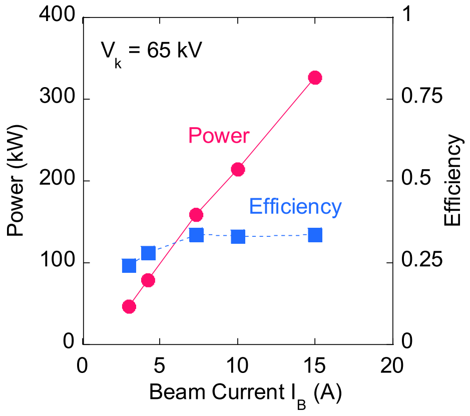

Fig. 1 Output power and efficiency as functions of beam current.

rent. The pulse width was set at 4 µs. The efficiency was higher than 30%, except in the low beam current region. The powers obtained are consistent with the design calculations, with α ranging from 1.1 to 1.3.

The radiation pattern was measured using an infrared camera as the increasing temperature profile on an absorber plate located in front of the vacuum window and oriented vertically relative to the radiation beam. A Gaussian like radiation pattern similar to that expected from the mode converter design calculations was obtained. The radiation pattern was somewhat elliptic and a small fraction of higher order modes was observed [10]. Quantitative mode content analysis is the next task.

Measurement of the oscillation frequency using a Fabry-Perot interferometer verified the single-mode oscillation of the design mode. The oscillation frequency was measured more accurately using a heterodyne receiver system. The measured frequency was 303.3 GHz when V_k = 62 kV and the magnetic field at the cavity B = 11.59 T. This frequency is equal to the designed $TE_{22,2}$ mode frequency to within an accuracy of the order of 10 MHz. The frequency variation with variation in operating conditions such as B and V_k was less than ±100 MHz. The frequency variation is related with a notch filter that is necessary to protect the receiver system from the gyrotron-frequency wave stemming from scattering off the vacuum vessel. The notch filter to be used for the CTS experiments in LHD has a center frequency of 303.3 GHz and the full rejection with of 500 MHz. The observed frequency variation around 303.3 GHz is safely smaller than this rejection width.

The pulse width was then extended. Figure 2 shows an oscillation with a pulse width of 80 µs. The output power is approximately 200 kW. The oscillation signal was measured using a pyroelectric detector in time integration mode. The linear increase in this signal indicates stationary oscillation through the pulse width. Although a long pulse width is preferable to increase the SN ratio, 80 µs is sufficient for CTS diagnostics in LHD. The SN ratio is proportional to the square root of the pulse width and a pulse width of the order of 100 µs will give a suitable SN ratio even for an incident power of 100 kW [3].

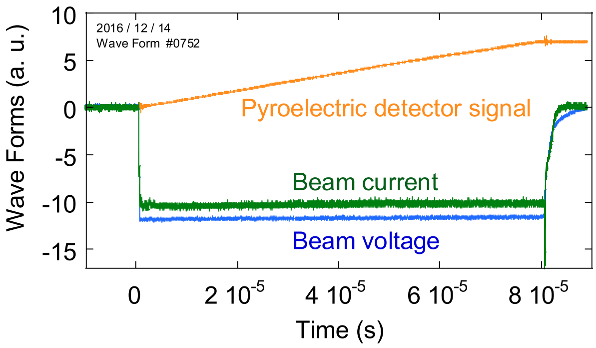

Fig. 2 Waveforms of an 80 µs oscillation. The beam voltage and beam current were set at 60 kV and 10 A, respectively.

The frequency spectrum is very narrow and stable across the pulse width. No competing modes were observed throughout the pulse width, including during the turn-on and the turn-off phases. Competing modes were also searched over a wide frequency band, ranging from 290 GHz to 312 GHz, using the same heterodyne receiver system. No oscillation other than the $TE_{22,2}$ mode was observed within the receiver system sensitivity limits.

A 300 GHz band pulse gyrotron was designed based on the concept that was used for a prototype gyrotron and was fabricated to act as a power source for CTS diagnostics in the LHD. Oscillation test results confirmed the single-mode oscillation of the $TE_{22,2}$ mode, which was the designed mode. The measured frequency is almost equal to the designed value of 303.3 GHz. The radiated beam has a Gaussian pattern, and power of more than 320 kW was obtained. Higher powers approaching 400 kW are expected with increased I_B after suitable conditioning.

Oscillation test results have proved that this gyrotron can be used in practice in CTS diagnostics in the LHD. Full details of the experimental results and a comparison with the design calculations will be published elsewhere.

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