Experiment for Over 200 kW Oscillation of a 295 GHz Pulse Gyrotron

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A high-power sub-THz gyrotron is under development as a power source of collective Thomson scattering diagnostic of fusion plasmas. It operates at a fundamental harmonic frequency of 295 GHz. A cavity which realizes stable and efficient single mode oscillation, an electron gun with an intense laminar electron beam, and an internal mode convertor are designed. A maximum oscillation power of 234 kW is achieved with a Gaussian like radiation pattern. The duration of 130 kW pulse is extended up to 30 microseconds, which is limited by the configuration of power supply.

Keywords: gyrotron, collective Thomson scattering, Large Helical Device

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This study aims at developing a high power gyrotron which is suitable for collective Thomson scattering (CTS) diagnostics [1] in large helical device (LHD). High-density plasmas in LHD require a high power probe wave of more than 100 kW in sub-THz region with pulse duration of around 1 ms to realize sufficient signal intensity and large scattering angles. At present, a 77 GHz gyrotron for electron-cyclotron heating has been utilized as a wave source [2]. However, delivering such a low frequency wave suffers from refraction, cut-off and absorption at the electron cyclotron resonance layer. Additionally, the signal detection is severely affected by background noise from electron cyclotron emission.

To resolve those problems, high power gyrotrons in 300~400 GHz range have been developed in FIR center, university of Fukui. At the beginning a second harmonic 389 GHz gyrotron was constructed using an existing 8 T superconducting magnet (SCM) [3]. While the $TE_{17,2}$ design mode can be excited with a power record of 83 kW, power saturation takes place at high beam currents [4]. Moreover, competing fundamental and other second harmonic modes prevent the stable operation [5].

To stably generate a much higher power, a fundamental harmonic oscillation was chosen with the frequency of 295 GHz, which is also suitable for the LHD. In this frequency range, a megawatt level oscillation with a highly oversized cavity has been reported [6]. However, the pulse duration was only a few microseconds, and severe mode competition was observed. The stable oscillation is of great importance for the practical wave source of CTS diagnostics. Therefore, a moderately oversized cavity is adopted to obtain simultaneously a single mode and high power oscillations at 295 GHz. A conventional cylindrical cavity which has 3.4 mm in radius and 9.0 mm in length was designed with $TE_{14,2}$ mode [7]. The neighboring modes of $TE_{3,6}$, $TE_{1,7}$ and $TE_{8,4}$ are well separated from $TE_{14,2}$, and no mode competition is predicted by the calculation of the beam-field interaction in the cavity. A power of more than 200 kW is expected with the beam voltage of $V_k = 65$ kV, the current of $I_b = 10$ A, and the pitch-factor (the ratio of transverse to longitudinal velocity of the electrons) of $\alpha = 1.2$ [8]. The ohmic and diffractive quality-factors are calculated as 15460 and 2480, respectively. In this case, the ohmic loss becomes about 10 kW/cm^2, however it is not a big problem for the pulsed operations with a duty ratio less than 10%.

The triode magnetron injection gun (MIG) was designed through EGUN simulations. Since a well laminated electron flow is formed, a high quality beam with small velocity spreads less than 5% is kept even for the higher beam currents [9, 10]. This gyrotron is equipped with a mode convertor consisting of a Vlasov launcher and three mirrors [11]. The vacuum window is made of single-crystal sapphire, the c-axis of which is perpendicular to the disk face to avoid double refraction. The thickness of the window is determined to maximize the wave transmission.

The 295 GHz gyrotron is mounted on a liquid He-free 12 T SCM, the room temperature bore of which is 100 mm (Fig. 1 (a)). The position of the tube has carefully adjusted for the SCM and auxiliary coils to guide the electron beam to the designed radius in the cavity. The oscillation test has

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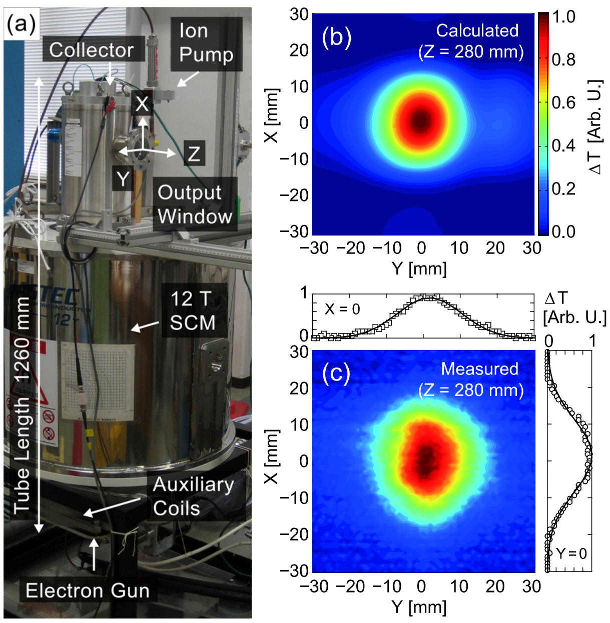

Fig. 1 (a) A photograph of fabricated gyrotron mounted on the 12 T superconducting magnet. (b) Calculated radiation pattern. (c) Measured radiation pattern. A Gaussian like distribution is successfully obtained.

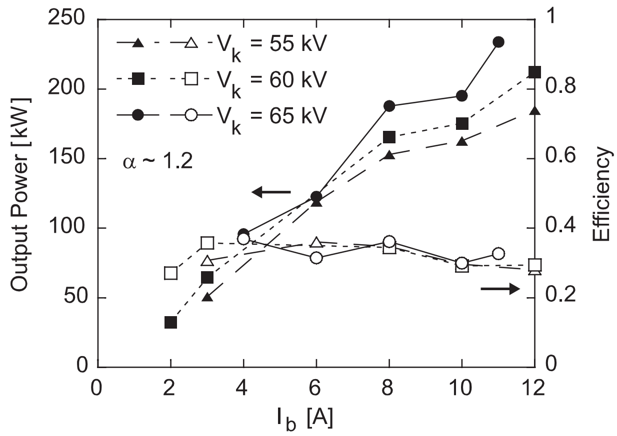

Fig. 2 Oscillation power and efficiency are plotted with closed and open symbols respectively as functions of the beam voltage and current. The maximum output power of 234 kW was achieved with the efficiency of 33%.

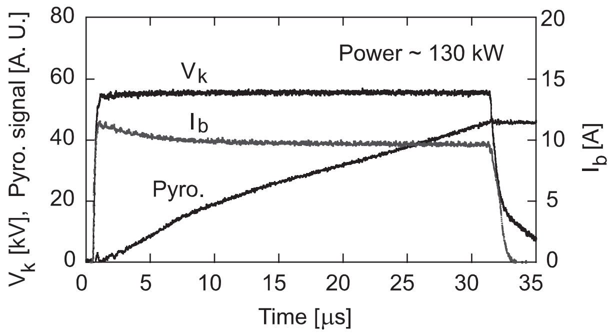

Fig. 3 The temporal evolutions of V_k, I_b and output signal. The pulse duration is extended up to 30 μs.

been carried out to find the optimum operation parameters with typical pulse duration and repetition frequency of 5 μs and 2.5 Hz, respectively. A single mode oscillation of $TE_{14,2}$ design mode was confirmed by frequency measurements with a Fabry-Perot interferometer. More accurate frequency measurement was performed with a heterodyne receiver system, and a sharp spectrum peak of 294 GHz was observed with a 3 dB bandwidth of 5 MHz.

The $TE_{14,2}$ mode is converted to a Gaussian beam by the internal mode convertor. Figure 1 (c) shows a radiation pattern as the temperature increase (ΔT) in a polyvinyl chloride plate of 1 mm in thickness placed perpendicular to the radiation direction at 280 mm away from the window. The measured pattern is similar to the calculated one (Fig. 1 (b)), and is confirmed to have highly Gaussian like distribution both in horizontal and vertical directions.

The output power was measured using a water load. Figure 2 shows the beam current dependence of the power and the efficiency for the beam voltages of 50 kV, 55 kV and 65 kV. The anode potential was set to provide the expected pitch factor of $\alpha\sim1.2$, which was found to be optimum to get the maximum power. The magnetic field was varied to find the maximum powers for each beam parameters. The power increases with both the beam voltage and current, and attains to 234 kW at V_k = 65 kV and I_b = 11 A, yielding an efficiency of 33%. Those beam parameters are limited by the power supply at the moment. Since no saturation in the power has occurred, higher powers are expected by enhancing the capability of the power supply.

Figure 3 shows the temporal evolution of the beam voltage, current and oscillation signal which was measured with a pyroelectric detector. The output power corresponds to the time derivative of the signal amplitude. A stable oscillation was demonstrated with the pulse duration up to 30 microseconds. The power at the steady state is about 130 kW. The extension of the pulse duration is mainly restricted by high voltage breakdown in air around the MIG. It is planned to employ the oil-insulation in the MIG region.

A high power 295 GHz pulse gyrotron for the CTS diagnostic in the LHD plasma is under development. Stable oscillation of $TE_{14,2}$ mode was demonstrated with a Gaussian like radiation pattern and a sharp frequency spectrum. The maximum output power of 234 kW was achieved with the efficiency of 33% in the short pulse operations. The present experiments have validated our design concept for a high power sub-terahertz pulse gyrotron. The limiting factor of the long pulse operation is the discharge around the MIG. This will be resolved in near future experiments. The final goal of the gyrotron development for CTS experiments is realizing an over 300 kW tube to ensure the sufficient power considering possible power losses in the transmission lines.

[1] Bindslev *et al.*, Phys. Rev. Lett. **97**, 205005 (2006).
[2] S. Kubo *et al.*, Rev. Sci. Instrum. **81**, 10D535 (2010).
[3] T. Notake *et al.*, Phys. Rev. Lett. **103**, 225002 (2009).
[4] T. Saito *et al.*, Phys. Plasmas **19**, 063106 (2012).
[5] T. Saito *et al.*, Phys. Rev. Lett. **109**, 155001 (2012).
[6] T.L. Grimm *et al.*, Phys. Fluids B **5**, 4135 (1993).
[7] Y. Yamaguchi *et al.*, IRMMW-THz 2012, Tue-A-3-5.
[8] T. Saito *et al.*, IRMMW-THz 2013, Mo5-3.
[9] Y. Yamaguchi *et al.*, Plasma Fusion Res. **7**, 1205004 (2012).
[10] Y. Yamaguchi *et al.*, Phys. Plasmas **19**, 113113 (2012).
[11] Y. Tatematsu *et al.*, J. Infrared Milli. Terahz Waves **33**, 292 (2012).