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FIRST PERFORMANCE TEST OF MULTI-FREQUENCY GYROTRON FOR ITER AND FUSION DEVICES

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Abstract

Multi-frequency gyrotrons can selectively generate a high power millimeter-wave at one of the frequencies. One of the advantages of using the multi-frequency gyrotrons on ITER and fusion devices is that the electron cyclotron heating location in plasma is adjustable by using the multi-frequency injection. It will compensate for an injection angle limitation of the launcher caused by the design limitations in 3-D space and in a neutron flux on the components. For such purpose, the multi-frequency gyrotron at 170 GHz, 203 GHz, and 236 GHz was developed by modifying the ITER prototype gyrotron. In the first performance test, the wave generations at the three frequencies were successfully demonstrated in the 500kW-3ms operations. Moreover, the output power achieved 1 MW at 236 GHz in the 1 ms operation and 870 kW at 203 GHz in the 100 s operation.

1. INTRODUCTION

The millimeter-waves injected into the plasma are absorbed by electrons where the wave frequency is about same as the electron cyclotron frequency. The electron cyclotron frequency is proportional to the magnetic field so that the requested gyrotron frequency also proportionally increases with that. The gyrotron frequency for ITER is 170 GHz [1], which is highest requested frequency in fusion devices. For future fusion devices with stronger magnetic field, the gyrotron frequencies are expected to be higher than 200 GHz [2]. According to the background and the advantage of using multi-frequency, QST started the development of the multi-frequency gyrotron at 170 GHz, 203 GHz, and 236 GHz (170/203/236-GHz gyrotron).

2. DESIGN OF 170/203/236-GHZ GYROTRON

As a first step, the ITER prototype gyrotron was modified to demonstrate the multi-frequency operation at high power. The developed 170/203/236-GHz gyrotron is shown in Fig. 1. The design will be improved step-by-step to achieve 1 MW of output power in the continuous wave with high oscillation efficiency of about 30%, such as 170-GHz gyrotron for ITER. For that purpose, the magnetron injection gun (MIG) of ITER prototype gyrotron was replaced to new one whose shape was redesigned to produce a high quality electron beam at the three frequencies. It is known that ITER gyrotron can generate 104 GHz, 137 GHz, 170 GHz and 203 GHz with specific cylindrical modes at the cavity [3]. These frequencies satisfy the multi-frequency condition described in Ref. 4, which are the high transmissivity at window, same radiation angle at the mode convertor, and close cut off frequency at the cavity. The multi-frequency condition indicated that the 236 GHz can be generated additionally without any changes in shapes of the cavity, mode convertor, mirrors, and thickness of output window. With this design, a heat load on the cavity is about a limit of 2 kW/cm^2 in the case of 1 MW long pulse operation at 236 GHz. It is the highest heat load removable by the present cavity design so that the cavity radius might need to be larger in the next development.

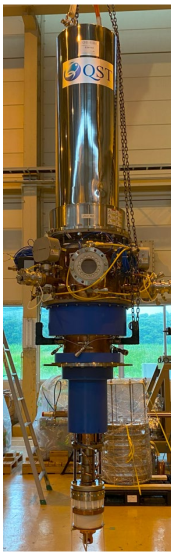

FIG. 1. 170/203/236-GHz gyrotron

3. PERFORMANCE TEST RESULTS

The performance of multi-frequency gyrotron was tested by using QST's gyrotron test stand with a new superconducting magnet (SCM) for the 236GHz-oscillation at around 9.5 T (Fig. 2). The SCM was designed by Kyoto Fusioneering and manufactured by JASTEC. The multi-frequency gyrotron successfully generated millimeter wave at 170, 203, and 236 GHz by adjusting the external magnetic field and voltage of each electrode. Those beam patterns were located at center of the output window as shown in Fig. 3. The shapes of beam patterns didn't show any strong sidelobes as expected in the design. These reduce a power loss in a transmission line and a risk of damaging the output window. The high power test was performed with parameters of beam current at 25 A, acceleration voltage at 70 kV, and pulse width at 3 ms. In the test, the output power and oscillation efficiency were about 500 kW and 27-29% at each frequency. The magnetic flux densities at the cavity were 6.58, 7.88, and 9.21 T for the 170, 203, and 236 GHz operations, respectively. Characteristics of output power and oscillation efficiency versus beam current were measured at 236 GHz (Fig. 4(a)). The output power increased with the beam current, and achieved the target value of 1 MW at 65 A in pulse operations of 1 ms. The measured gyrotron frequency was approximately 236.1 GHz (Fig. 4(b)). The optimum acceleration voltage became larger with the increase of beam current. The acceleration voltages were 70 kV at 25 A and 35 A, 75 kV at 50 A, and 78 kV at 65 A. The oscillation efficiency decreased from 27% to 20% with the increase of beam current. The reason is under investigation. In the case of 203 GHz operation, long pulse and high power operations were performed. The 750kW-100s long pulse high power operation was successfully achieved with the oscillation efficiency of 27%. The efficiency was not drastically degraded with the increase of beam current and pulse width. In the last day of this campaign, the output power achieved 870 kW in a 100-s operation (Fig. 5(a)). The waveform in Fig. 5(a) shows RF signal measured at one of the miter bend in the transmission line. The output power of 870 kW was calculated from an increase of cooling water temperature of the dummy load. The gyrotron frequency was maintained at approximately 202.9 GHz for 100 s (Fig. 5(b)). There was a brief interruption for approximately 72 s to 73 s due to a mode shift and recovering from that. Mode shifts can be avoided by adjusting operation parameters.

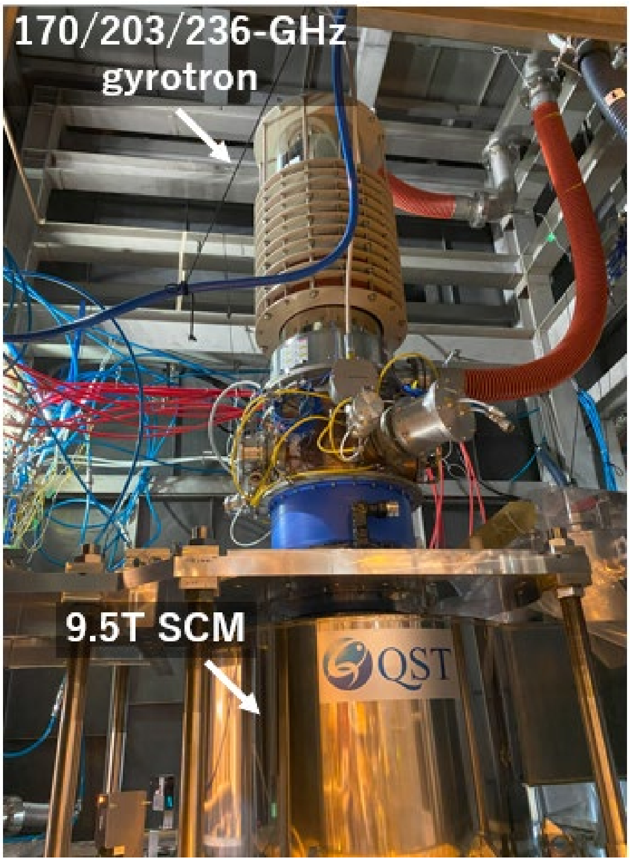

FIG. 2. The multi-frequency gyrotron (170/203/236 GHz) and SCM (up to 9.5 T) newly installed into QST's gyrotron test stand.

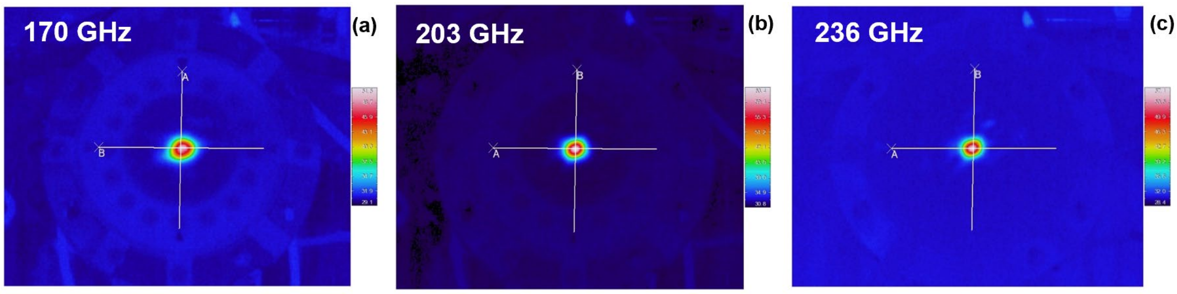

FIG. 3. Measurement of beam patterns at the output window at a) 170, b) 203, and c) 236 GHz.

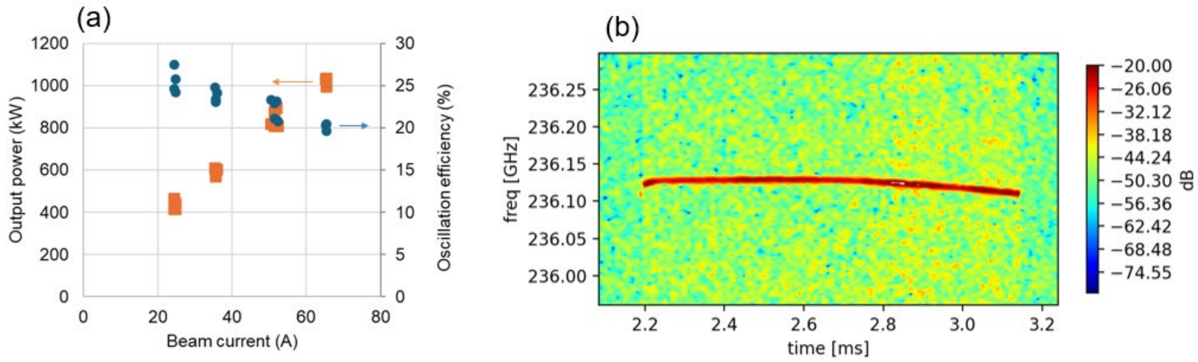

FIG. 4. Performance test results at 236 GHz. a)Characteristics of output power and oscillation efficiency versus beam current measured in the short pulse operations for 1 to 3 ms. b)Measured gyrotron frequency at the 1-MW operation.

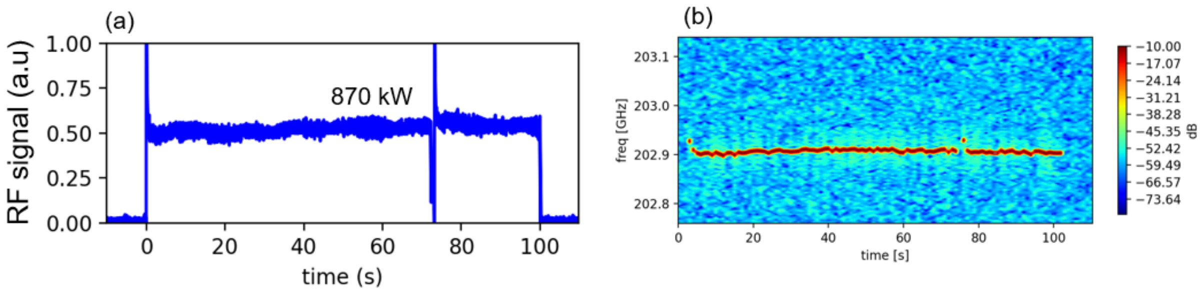

FIG. 5. Performance test result at 203 GHz. a) RF signal measured at the miter bend. Output power achieved to 870 kW in the long pulse operation of 100 s. b) Gyrotron frequency.

4. CONCLUSION

The target of multi-frequency operations at 170 GHz, 203 GHz, and 236 GHz with high power were successfully demonstrated by modifying the MIG of ITER prototype gyrotron. The output power achieved 1 MW at 236 GHz in the 1 ms operation. Moreover, the pulse width was successfully extended to 100 s at 203 GHz, and the output power achieved 870 kW. These initial results show a possibility of realizing the multi-frequency high power gyrotron for fusion devices.

REFERENCES

[1] IKEDA, R., et al, Multi-frequency, megawatt-power gyrotron to facilitate a wide range of operations at ITER, Nucl. Fusion **63** (2023) 066028.

[2] ODA, Y., et al, Design activities of ECH/CD system for JA DEMO, AIP Conf. Proc. **2984** (2023) 030002.

[3] IKEDA, R., et al, Multi-Frequency, MW-Power Triode Gyrotron Having a Uniform Directional Beam, J. Infrared Millim. Terahertz Waves **38** (2017) 531.

[4] KAJIWARA, K., et al, Development of Dual-Frequency Gyrotron with Triode Magnetron Injection Gun, Appl. Phys. Express **4** (2011) 126001.