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High-power, Long-pulse Oscillation of a Dual-frequency Gyrotron for JT-60SA
JT−60SA用2周波数ジャイロトロンの高出力・長パルス発振

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A high-power long-pulse dual-frequency gyrotron, which can be operated at both 110 GHz and 138 GHz independently, was successfully developed for electron cyclotron heating and current drive in JT-60SA. The output power of 1 MW and the pulse length of 100 s were obtained at both frequencies with the high oscillation efficiency (not including an efficiency enhancement by collector potential depression) of 34% (110 GHz) and 32% (138 GHz), respectively. An optimization of the electron pitch factor was a key to obtain the high efficiencies, and oscillation characteristics of the gyrotron were experimentally confirmed.

1. Introduction

An electron cyclotron heating and current drive (ECH/ECCD) system is one of the important sub-systems of tokamak devices due to its unique capability of highly localized electron heating and current drive. In JT-60SA, high-power, long-pulse gyrotrons are required for ECH/ECCD system, which will have the total injection power of 7 MW and the pulse duration of 100 s using 9-gyrotrons [1]. In order to enable ECH/ECCD at many experimental scenarios of JT-60SA, a dual-frequency gyrotron [2-5], which can operated at both 110 GHz and 138 GHz, has been developed in Japan Atomic Energy Agency [6]. The frequency of 110 GHz is effective for ECH/ECCD at the toroidal magnetic field B_t of 1.7 T while the frequency of 138 GHz is effective at B_t ~ 2.3T [7]. Both frequencies are injected as second harmonic resonance waves. In this presentation, we report resent results on the high-power, long-pulse operations of the dual-frequency gyrotron. Moreover, oscillation characteristics of the gyrotron investigated by parameter survey are reported.

2. High-power, long-pulse oscillations

High-power, long-pulse operations of the dual-frequency gyrotron were carried out in 2014. The maximum output energy had been limited by temperature and vacuum pressure increase in the transmission line (TL) due to insufficient cooling capability of the TL and the large amount of outgas from a dummy load. By improving the cooling capability of the TL and by continuing conditioning operations, the maximum injection energy of 100 MJ has been achieved. The gyrotron output power, $P_{gyro.}$, of 1 MW for 100 s and 0.5 MW for 198 s have been obtained, so far, at both frequencies of 110 GHz and 138 GHz [8]. Figure 1 shows the temporal evolution of the voltages applied to the cathode (V_k), anode (V_a) and body (V_b) electrodes, beam current (I_{beam}), RF signal detected by a diode detector installed at a power

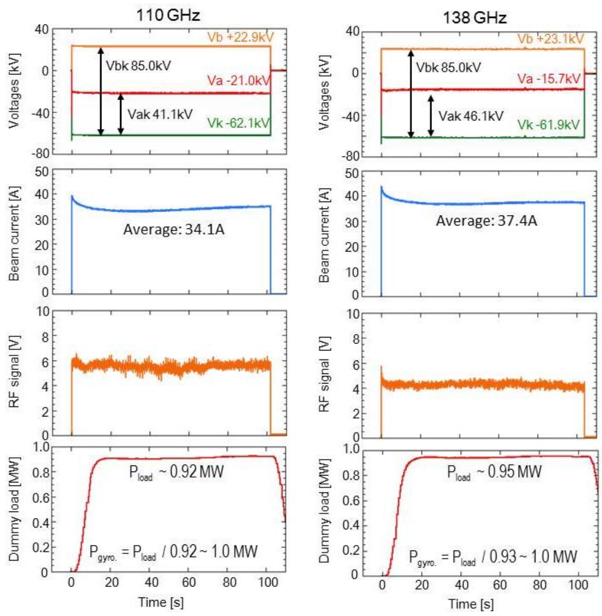

Fig.1. Time traces of the beam current, voltages applied to the cathode, V_k, anode, V_a, and body, V_b, electrodes, rf signal detected by a diode detector installed at the directional coupler of the power monitor miter-bend, calorimetrically measured power at the dummy load, P_{load}, for oscillations of the gyrotron output power, $P_{gyro.}$, of 1 MW for 100 s at 110 GHz and 138 GHz.

monitor miter-bend in the TL, the calorimetrically measured power at the dummy load (P_{load}). The acceleration voltage, V_{bk}, was 85 kV at both oscillations. The oscillation efficiencies (not including collector potential depression) were 34% and 32 % at 110 GHz and 138 GHz, respectively. This efficiency is sufficiently high for long-pulse operation at > 1 MW. Since the beam current reduction due to cathode cooling was stabilized within 100 s by means of a pre-programmed heater control system developed in JT-60U [9], the oscillation condition will not be changed for longer pulse oscillations. Moreover, it was confirmed that the cavity heat load at 110 GHz was reduced by increasing operating mode number from $TE_{22,6}$ to $TE_{22,8}$ in comparison with the previous gyrotron, which achieved 1.5 MW/4s, 1.4 MW/9s [10]. Consequently, the higher power (~ 2 MW) oscillations will be possible by increasing the beam current by the dual-frequency gyrotron at 110 GHz.

3. Oscillation characteristics

One of the key points of high-power, long-pulse operations of the dual-frequency gyrotron is to obtain high efficiency by optimizing electron pitch factor at each frequency/mode as well as to optimize shape of the internal components (cavity, mode convertor, window and gun) [8]. The dual-frequency gyrotron equipped with a triode type magnetron injection gun (MIG), by which the electron pitch factor can be changed by changing the anode voltage. Figure 2 shows contours of the output power (50 kW each) at various $V_{ak} = V_k - V_a$ and the cavity magnetic field B_c. In order to obtain the same pitch factor at the different B_c, the higher V_{ak} is required at the higher B_c. Consequently, the optimum V_{ak} at 138 GHz is higher than that at 110 GHz by ~5 kV. The optimization of the pitch factor by the triode MIG will be effective to obtain high efficiency even for step tunable multi-frequency gyrotrons required in DEMO.

As seen in Fig. 2, the operation window of 138 GHz is narrower than that of 110 GHz. Since the operating mode at 138 GHz ($TE_{27,10}$) is higher than that at 110 GHz ($TE_{22,8}$), the competing modes might be easily appeared. It is also mentioned that the maximum efficiency at 138 GHz was limited by an arcing in the gyrotron, which might be caused by a counter rotating mode, during start up process of the power supply (~ 100 ms); it appeared before the nominal voltages were applied to the electrodes. On the other hand, the maximum efficiency at 110 GHz was limited by unstable oscillation of the target mode after the power supply was stabilized. Thus, it may be possible to increase the oscillation

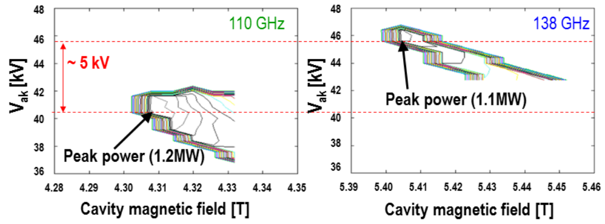

Fig.2. Contour of the gyrotron output power (50 kW each) at 110 GHz (top) and 138 GHz (bottom) obtained by changing the anode-cathode voltage (V_{ak}) and the cavity magnetic field for 2 s pulses. The acceleration voltage and the time averaged beam current are 85 kV and 40.5 A, respectively.

efficiency at 138 GHz by modifying the start-up pass of the power supply toward nominal operation parameters.

4. Conclusion

High-power, long-pulse and high-efficiency oscillations of 1 MW for 100 s (>30%) were successfully demonstrated by the dual-frequency gyrotron at both 110 GHz and 138 GHz. This result fully satisfied the target for JT-60SA. It was experimentally confirmed that the anode voltage control by means of the triode MIG was effective to obtain high efficiency for the dual-frequency gyrotron. The operation characteristics of the gyrotron at each frequency/mode were experimentally investigated. It was found that the operation parameter (anode voltage, cavity field) window to excite the target mode at 138 GHz was narrower than that at 110 GHz, so far, while further expansion of the operation window and increase in the oscillation efficiency at 138 GHz will be possible by changing start-up pass of the power supply.

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