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New Results of Development of Gyrotrons for Plasma Fusion Installations & Development of Multi-Frequency Mega-Watt Gyrotrons for Fusion Devices in JAEA & Development of Over MW Gyrotrons for Fusion at Frequencis from 14 GHz to Sub-terahertz

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A. Gyrotrons for plasma fusion installations usually operate at frequencies 40-170 GHz. Requested output power of the tubes is about 1 MW and pulse duration is between seconds and thousands seconds. To provide operation with indicated parameters the gyrotrons have very large transverse cavity sizes, output barrier windows made of CVD diamond discs, effective collectors with particle energy recovery.

In ITER installation there will be 24 gyrotron systems with 1 MW power each. Russian contribution consists of 8 gyrotron systems. ITER requirements are: frequency 170 GHz, 1 MW power, 1000 s pulse duration, high efficiency of the gyrotrons over 50%, possibility of power modulation with frequency up to 5 kHz, compatibility of the gyrotron complex with ITER control system. In May, 2015 a Prototype of ITER Gyrotron System was completed and its operation was demonstrated. The system consists of gyrotron oscillator, liquid-free superconducting magnet, supplementary magnets, several electric power supplies, cooling systems control and protection systems, and other auxiliary units. The tests were performed in presents of ITER IO and ITER RF DA representatives. In October, 2015 Final Design Procedure for the gyrotron system was successfully passed.

High-level parameters were also achieved with long-pulse 140 GHz gyrotrons developed for EAST and KSTAR installations. Significant results were shown on the way to 1.5-2MW, CW gyrotrons. The development of higher frequency (230-700 GHz) gyrotrons for future plasma installations and for plasma diagnostics began. Novel ideas were proposed to enhance gyrotron operation.

B. Mega-watt gyrotrons with frequency tuning have become essential devices in fusion science to perform effective EC H&CD. JAEA is developing two types of multi-frequency gyrotrons equipped with a triode magnetron injection gun for ITER and JT-60SA. A TE31,11 mode, which is a candidate mode for 170 GHz oscillation, has sufficient margin for cavity heat-load in 1 MW operation, and it has a great advantage for multi-frequency oscillation. In the JT-60SA project, EC H&CD by second harmonic EC waves are planned using nine sets of 110 GHz/138 GHz dual-frequency gyrotrons to broaden the experimental research area. In FEC2014, demonstrations of 1 MW oscillations for 2 s at 170 GHz/137 GHz/104 GHz with the ITER gyrotron and achievement of 1 MW oscillations for 100 s at 110 GHz /138 GHz in the JT-60SA gyrotron were reported as world records. After FEC2014, oscillation methods to improve the efficiency at 170 GHz for ITER requirements and higher frequency oscillation for the demo-class reactor were investigated. For the JT-60SA gyrotron, the operation area was expanded to surpass maximum performance (1.5 MW/4 s) of the previous JT-60 110 GHz gyrotron. TE31,11 mode oscillations were often prevented by adjacent counter-rotating (ctr-) modes such as TE29,12, and TE28,12 modes. By introducing active anode-voltage control and beam-radius control to suppress adjacent counter-rotating modes, start-up of TE31,11 mode becomes stable and the overall efficiencies achieved ˜ 50 % up to 1.1 MW. In looking ahead to a future gyrotron for the demo-class reactor, 203 GHz oscillation of higher-order volume mode (TE37,13) was performed for the first time by taking advantage of the multi-frequency gyrotron feature. In preliminary testing at 203 GHz, 0.9 MW for 0.3 ms and 0.42 MW for 5 s were demonstrated. ITER gyrotron having mega-watt-class power at four frequencies in wide range over

100 GHz was developed. High power gyrotron development toward 1.5 –2 MW oscillation for several seconds has been carried for further extension of the experiment regime of high performance plasma in JT-60SA. In a test conducted in 2015, achievements of 1.8 MW/1.2 s at 110 GHz (TE22,8 mode) in non-coaxial type gyrotron and high-power oscillation of 1.3 MW/1.3 sat 138 GHz (TE27,10 mode)and 1 MW/1 s of 82 GHz (TE17,6 mode) have been demonstrated as a new world record.

C. Megawatt (MW) gyrotrons with a wide frequency range from 14 to 300 GHz are being developed for the collaborative Electron Cyclotron Heating (ECH) study of advanced fusion devices and DEMO reactor. (1) In the first experiment of 300 GHz gyrotron, an output power of over 0.5 MW with TE32,18 single-mode was achieved with a pulse width of 2 ms. This is the first report of MW level oscillation with the DEMO-relevant ECH gyrotron mode. It was also found that the reflection at the output window affects the oscillation mode determination. (2) A new record of the 28 GHz gyrotron output of 1.38 MW was obtained. The fabrication of a newly designed tube aimed at a dual-frequency output power of 2 MW at 28 GHz (0.4 MW CW) and 1 MW at 35 GHz has begun, with all components ready for assembly. Before installing a double-disk window in the dual-frequency gyrotron, we confirmed the dependence of reflective power on the coolant thickness including the reflective power less than 2 % by the cold test using a Gunn diode power of 1 W and the hot test using the gyrotron output power of 600 kW. (3) Based on the successful results of 77 and 154 GHz LHD tubes, the new design of a 154/116 GHz dual-frequency gyrotron with output of over 1.5 MW has been presented.

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