

Achievement of 1.5 MW, 1 s Oscillation by the JT-60U Gyrotron

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High-power gyrotrons are required for electron cyclotron heating/current drive in high-performance plasma experiments. In Japan Atomic Energy Agency, the operation conditions of the JT-60U gyrotron, which was originally designed as a 1-MW gyrotron, were optimized in order to achieve high-power and long-pulse operation with some modifications of the gyrotron components. As a result, the output power level of 1.5 MW for 1 s was successfully achieved.

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Gyrotrons are used for electron cyclotron heating (ECH)/current drive (ECCD) as high-power millimeter-wave sources in high-performance plasma experiments. ECH/ECCD is being recognized as an important tool owing to its ability of efficient electron heating and suppression of neo-classical tearing mode instabilities [1]. In ITER, about 20 MW of ECH/ECCD is required [2]. In JT-60SA, 7 MW of ECH/ECCD has been planned, and an oscillation of 1 MW, 100 s per gyrotron is required [3]. For the simplification of ECH/ECCD systems that would result in a reduction in construction, operation, and maintenance costs, R&D works for a higher-power gyrotron, such as a 2-MW gyrotron, have been continued [4]. Moreover, the capability of higher-power operation results in significant reliability for 1-MW operation. Up to now, an oscillation of 2.14 MW, 1 ms at 140 GHz was demonstrated in Forschungszentrum Karlsruhe as a high-power gyrotron [5], and an oscillation of 1 MW, 800 s at 170 GHz was demonstrated in Japan Atomic Energy Agency (JAEA) as a high-power and continuous-wave (CW) gyrotron [6]. On the other hand, a pulse length from 0.1 to several seconds with high power is required in the current tokamak experiments, such as JT-60U. However, a 0.1-s oscillation had only been achieved at a power level of 1.5 MW as shown in Fig. 1 [7]. In JAEA, high-power and long-pulse oscillation experiments by using the latest JT-60U gyrotron have been carried out in order to achieve a power level of 1.5 MW and a pulse length of more than 1 s. As a result, an oscillation of 1.5 MW, 1 s has successfully been achieved by the fine optimization of operation parameters. In this paper, the first results of the oscillation experiment of 1.5 MW for 1 s and the future plans for gyrotron improvements are described.

In JT-60U, four 110-GHz gyrotron systems have been installed in the RF room. These gyrotrons are featured by

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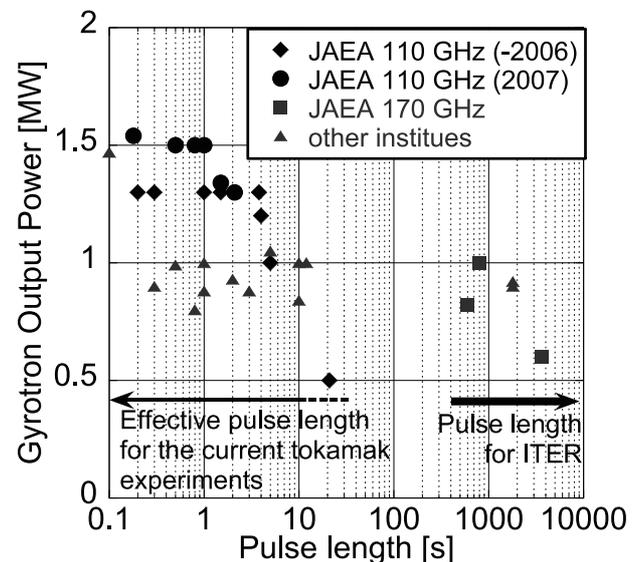


Fig. 1 Gyrotron output power vs. pulse length (> 0.1 s) achieved in the world.

a triode-type magnetron injection gun, a diamond window, and a collector-potential depression technology. The oscillation mode is $TE_{22,6}$, and an oscillation of 1 MW, 5 s had already been achieved by the original gyrotrons with an improved beam tunnel [8]. Further, these gyrotrons have been usually operated at an oscillation power of ~ 1 MW for a pulse length of several seconds with an efficiency of 30 ~ 40%. In order to achieve a longer pulse and a higher power, some modifications have been introduced into the latest gyrotron. An Si_3N_4 ceramic (Kyocera SN287) DC-break has been introduced into the gyrotron instead of an alumina ceramic DC-break owing to the higher thermal strength. There is a bellows in the gyrotron to move the last mirror that enables to adjust the RF beam angle. In

order to protect the bellows from heat flux caused due to a stray RF, a cover has been newly installed around the bellows. In addition, the flow of cooling water at the cavity has been increased by about 20%. The heat load on the cavity wall has enough margin at 1 MW for the original gyrotrons. Then, a short-pulse oscillation of 1.5 MW had already been demonstrated [9]. As the next step of a high-power oscillation, experiments that aimed at a pulse length of 1 s with a power level of 1.5 MW were carried out by using the latest gyrotron in the RF room of JT-60U in July 2007. Figure 2 shows a schematic view of the experimental setup. In order to measure the output power, the oscillated RF was transmitted into a dummy load through a matching optics unit (MOU), and three miter bends with corrugated waveguides (ϕ 31.75 mm) in this experiment. The length of the whole transmission line was about 13 m. The dummy load consisted of a pre-waveguide load (1.5 MW, CW, and 50% attenuation), a main waveguide load (1.0 MW, CW, and 75% attenuation), and a tank load (1.0 MW, 5 s). The absorption efficiency at the pre-waveguide load and the transmission efficiency of the transmission line was calibrated by a calorimetric load. Therefore, the time-averaged output power was evaluated by the increase of the cooling water temperature of the pre-waveguide load taking into account the transmission and absorption efficiencies. After the conditioning operation with low power (\sim 500 kW), a high-power ($>$ 1 MW) oscillation was started with a short pulse of several 10 ms. At first, the body-power-supply (BPS) voltage (V_{BPS}), anode-body voltage (V_{ab}) and superconducting magnet current (I_{Bc}) were set at 86 kV, 43.2 kV and 103.80 A, respectively. The collector current (I_c) was about 60 A. The anode-cathode voltage and the magnetic field strength are sensitive parameters owing to the significant effect of a pitch factor on the oscillation efficiency. Therefore, V_{ab} and I_{Bc} were mainly optimized, and an adjustment of the order of 0.01 A was required for I_{Bc} . At the end of the three-day high-power conditioning and optimizing operations, a stable oscillation of 1.5 MW for 1.0 s was successfully achieved with a time-averaged efficiency of about 40%. In this oscillation, V_{BPS} , V_{ab} and I_{Bc} were

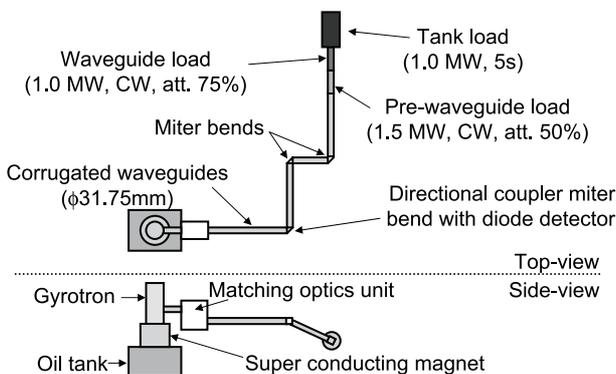


Fig. 2 Schematic view of the experimental set up.

86 kV, 42.8 kV, and 103.51 A, respectively, and the peak I_c was 62.8 A. Figure 3 shows the time evolution of voltages on the body (V_b), anode (V_a) and cathode (V_k); the currents on the collector (I_c), anode (I_a), and body (I_b); and the RF signal detected at the directional coupler. The time evolution of temperatures measured by thermocouples at the cavity and the middle-part of the collector and the temperature of the DC-break cooling water are also shown in Fig. 4. In this oscillation, nothing that obviously suggested the boiling of the cooling water or vacuum leakage was observed. In the above experiments, the pulse length of 1 s was just a setting parameter: it was not limited by any interlock signals. Therefore, it will be possible to obtain a longer pulse such as a 2-s pulse by making more fine adjustments. However, in order to achieve a longer-pulse operation, we need to pay attention to the heat load on components. Therefore, more detailed temperature mea-

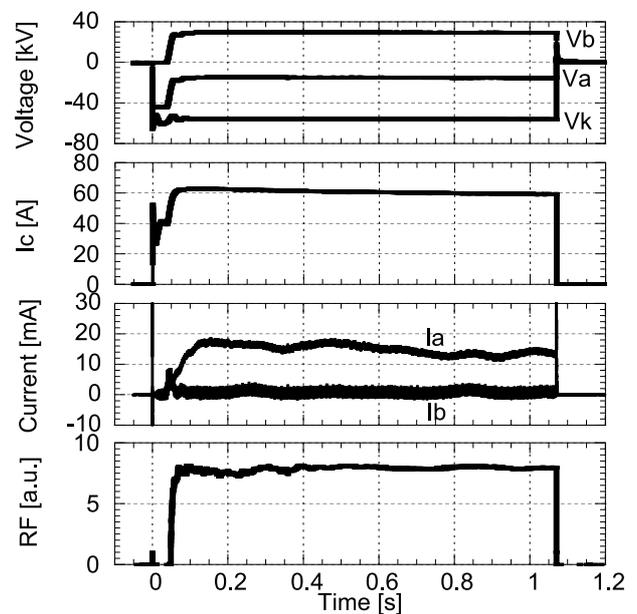


Fig. 3 Time evolution of the voltages on cathode (V_k), anode (V_a) and body (V_b), the currents on collector (I_c), anode (I_a) and body (I_b), and the RF signal detected at the directional coupler.

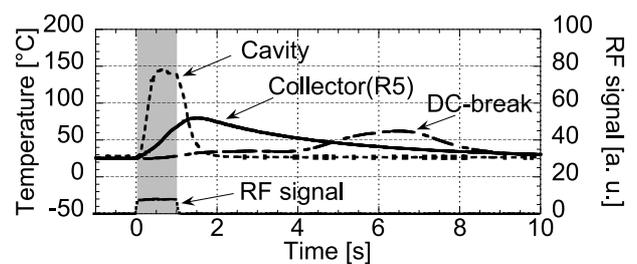


Fig. 4 Time evolution of DC-break cooling water temperature and temperatures measured by thermocouples at the cavity and the middle-part of the collector.

surements of the collector and the DC-break in the case of the 1.5 MW, 1 s oscillation will be carried out soon in order to estimate the temperatures in the case of the longer pulse.

On the other hand, the conversion efficiency of the mode converter of the JT-60U gyrotrons, which equips a single helical-type quasi-optical radiator, is not very high as compared to that of the latest 170-GHz gyrotron that has already achieved an oscillation of 1 MW, 800 s [6, 10]. Therefore, the mode converter will be improved by the same design scheme as that of the 170-GHz gyrotron. The improved mode converter will lower the heat load on each component. In addition, it will provide higher efficiency: therefore, the beam current and the acceleration voltage can be kept lower. This improvement will provide more reliability of operation and enable the longer-pulse oscillation in JT-60U. Such an improvement will be introduced into one of the original gyrotrons along with the replacement of the alumina DC-break with an Si_3N_4 one and some

other minor changes. The improved gyrotron will be tested in spring 2008, and operated in the JT-60U experimental campaign.

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