Long Pulse and High Power Repetitive Operation of the 170 GHz ITER Gyrotron

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Details of the first repetitive operation of a 170 GHz long pulse gyrotron with quasi-CW (400 s pulse width) and high power are presented. The interval between pulses was 30 minutes, which matches the ITER operation scenario. The repetitive operation continued for 5 hours without problems and terminated as planned. The pressure inside the gyrotron returned to the original level after 20 minutes. This was the first operation for the high power gyrotron system applicable to ITER.

Keywords: gyrotron, ITER, ECH/ECCD, high power operation, long pulse operation

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In ITER, an electron cyclotron heating and current drive (EC H&CD) system with injection power of 20 MW will be adopted. As a power source 170 GHz, 1-MW gyrotrons are required [1–3]. Recent progress of the gyrotron and the EC H&CD system can be found in Refs. [4–9]. In Japan Atomic Energy Agency (JAEA), a gyrotron has been developed for ITER. The ITER requirement, i.e., an RF power of 1 MW, RF power generation efficiency of higher than 50%, and a pulse width of 500 s was satisfied in 2006, as reported in Refs. [10] and [11]. The next important study is to show a realistic repeatability of high power and long pulse operation for application to the experiments in ITER. In this letter, ITER relevant repetitive operation is described.

The schematic view of the gyrotron is shown in Fig. 1. It is a triode-type, depressed collector gyrotron with a diamond window [12]. The cavity mode is $TE_{31,8}$ and the frequency is 170 GHz. The cathode heater current, the anode voltage, and the magnetic field can be changed during the pulse by preprogrammed command or manual control. The output RF power couples with a waveguide (HE_{11}) through a matching optical unit that includes two phase correcting mirrors. The RF power is absorbed by a 1.2-MW dummy load and a pre-dummy load placed at the end of the transmission line.

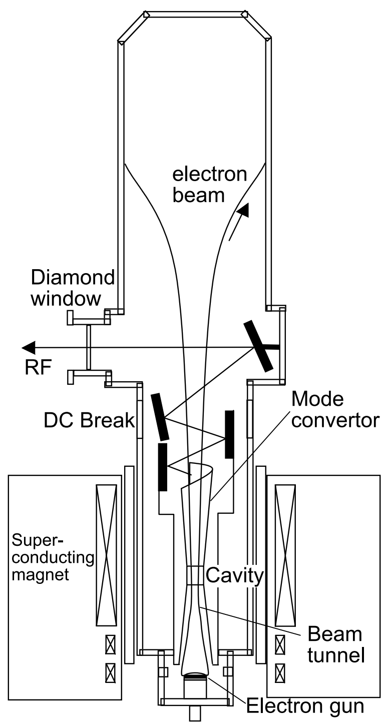

Fig. 1 Schematic view of the gyrotron in JAEA.

The waveforms of the repetitive operation are shown in Figs. 2 (a)-(e). As shown in the figures, 400-s operation was attempted every 30 minutes. Figures 2 (a) and (b) show the time behavior of the beam current and the voltages of the cathode, anode and body. The output power estimated from the temperature increase of the cooling water of the 1.2-MW dummy load and pre-dummy load is shown in Fig. 2 (c). The difference in the power throughout the five hours of operation was ±25 kW. The variation of the power was caused by a slight change of the beam current. One of the reasons for this change is shot-by-shot modification of the cathode heater voltage in order to find the best preprogrammed control. Figure 2 (d) shows the collector temperature measured by a thermocouple that is installed 3 mm from the inner surface. The pressure inside the gyrotron returned to the original level after 20 minutes, as shown in Fig. 2 (e).

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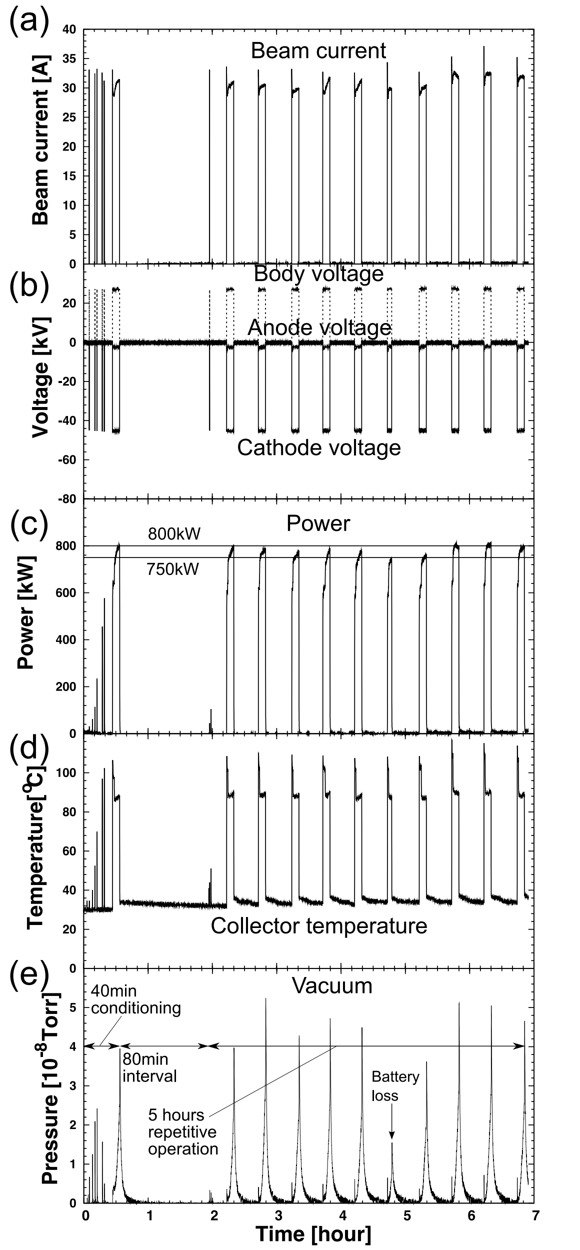

Fig. 2 Waveforms for the five hours of repetitive operation: (a) beam current, (b) body, anode and cathode voltage, (c) output RF power, (d) collector temperature, (e) pressure inside the gyrotron.

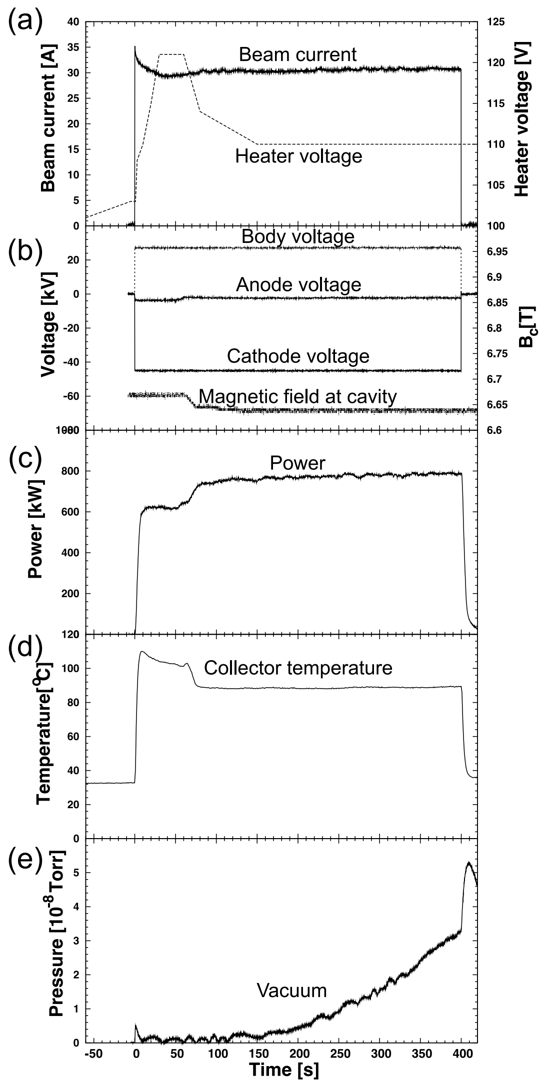

Fig. 3 Typical waveform of the repetitive operation: (a) beam current and applied voltage of cathode heater, (b) body, anode and cathode voltage. The magnetic field at the cavity is also shown, (c) output RF power, (d) collector temperature, (e) pressure inside the gyrotron.

At the beginning of operation, a conditioning procedure was carried out on the gyrotron. After performing a series of 10-s shots, the first 400-s shot was performed with no trouble. Next, ten 400-s shots were attempted after a 80 minutes break. No conditioning was required between the shots. The 6th shot (shown by the vertical arrow in Fig. 2 (e)) was terminated at 239 s due to a depleted battery on the current monitor, which triggered an interlock system. However, this shot termination had no effect on the following shots.

Figures 3 (a)-(e) show typical waveforms for the repetitive operation. Figure 3 (a) shows the beam current and the applied voltage of the cathode heater as a function of time. Here, the heater voltage was controlled by preprogrammed commands. The beam current profile starts around 35 A and quickly decreases to around 29 A due to cathode cooling by electron emission. Forty-five seconds later, the beam current decreases to a minimum value, after which it increases until the 100 s. This is most likely because the beam current does not respond to the heater current immediately. Figure 3 (b) shows the waveforms of the voltages. The anode voltage is preprogrammed to increase about 1.7 kV between 50 s and 60 s. After that, the magnetic field (shown in Fig. 3 (b)) is manually decreased in order to operate in the hard excitation region [10]. The output power increases as the magnetic field decreases, as shown in Fig. 3 (c). After $t \sim 100$ s, 800 kW output power was obtained. Here, the oscillation efficiency is 35% and the total efficiency, including the depressed collector, is 56%. The operation is targeted for a power of 800 kW instead of 1 MW to have enough margin of the heat load to the cavity. One-megawatt long-pulse operation is planned for a next gyrotron, which will be operated with a $TE_{31,12}$ cavity mode and will be capable of a peak power of 1.5 MW. The measured stray RF [11] inside this gyrotron is 23 kW, which is 2.9% of the output power. Figure 3 (d) shows the collector temperature measured by the highest reading thermocouple of the embedded array. Temperature decreases as power increases, which is thought to be due to an increase in the oscillation efficiency. The highest temperature of the collector is less than 120°C. Figure 3 (e) shows the pressure inside the gyrotron. It is not saturated and remains at less than 6×10^{-8} Torr. Typically, the pressure inside the gyrotron saturates after 800 s [11].

In conclusion, ITER-relevant, repetitive, long-pulse operation has been consistently demonstrated. Five hours of repetitive operation with 30 minute intervals has been successfully achieved without any major problem. During the 5 hours of operation, 800 kW output power is maintained, the oscillation efficiency is 35%, and the total efficiency including the depressed collector, is 56%. The pressure inside the gyrotron returns to the original level after 20 minutes. The results show the clear prospect for the application of 170 GHz gyrotrons to heating and current drive experiments on ITER.

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