Progress of high power and long pulse ECRF system development in JT-60

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Abstract. Gyrotron output power of 1.5 MW for 4 s, which was the longest pulse length in the world at an output power of ~ 1.5 MW, was recorded on the JT-60 ECRF system by developing a new operation technique. The electron pitch factor was optimized within ~ 0.1 s after the start of the gyrotron operation by active control of the anode voltage. This technique led to enhancement of the oscillation efficiency for long pulse and then the collector heat load was reduced by 20% with respect to the conventional operation (without active control). The reduced collector heat load at 1.5 MW operations was acceptable for steady state operation. Another progress was done on a new gyrotron with an improved mode convertor which reduces the stray radiation in the gyrotron which had so far hindered long-pulse operations through unacceptable heat load. It was confirmed that the stray radiation was reduced to 1/3 of the original gyrotron which will be acceptable for steady state operation. A conditioning operation of the improved gyrotron is proceeding up to 30 s at 1 MW. These progresses significantly contribute to enhancing the high power and long pulse capability of the ECRF system toward JT-60SA, where the total output power of 9 MW for 100 s is planned.

1. Introduction

On JT-60 Super Advanced (JT-60SA), which is a fully superconducting tokamak utilizing the JT-60 facilities, a high power Electron Cyclotron Range of Frequency (ECRF) system of 110GHz, 9 MW, 100 s is planned for local heating, current drive and plasma initiation. The JT-60 ECRF system (110 GHz, 4MW, 5 s) [1] is to be upgraded with increasing the number of gyrotrons from four to nine. Since a high-power gyrotron with the output power exceeding 1 MW is a key to enhance the ECRF system further, a high power operation at 1.5 MW has been pursued on the JT-60 ECRF system.

An essential issue to achieve high power and long pulse gyrotron oscillation is to reduce heat load in the gyrotron. The major heat load in a gyrotron is classified into three types: (a) heat load on the cavity resonator, (b) heat load on the collector and (c) heat load due to diffraction loss, especially a heat load on the DC-break (DCB) between collector and body electrodes. The heat load on the cavity resonator depends on the generated RF power, $P_{\rm rf}$, and the operating cavity mode. On the 110 GHz gyrotron with a conventional cylindrical cavity operating at $TE_{22,6}$ mode, we had already demonstrated an oscillation of 1.5 MW for 1 s [2] and the cavity temperature was saturated at ~ 150 °C within 1 s, so that the heat load on the cavity resonator was applicable for further long pulse operation. However, it was found that the heat load of the collector and the heat load due to diffraction loss in the gyrotron were too high to extend the pulse length. Therefore, developments for long pulse operation have been carried out to solve these issues.

In this paper, a new operation technique to reduce the collector heat load is shown in Sec. 2. Another progress on a new gyrotron to reduce the diffraction loss toward long pulse operation of 100 s in JT-60SA is described in Sec. 3. The modification of the JT-60 ECRF system (FIG. 1) to test the new gyrotron is also mentioned.

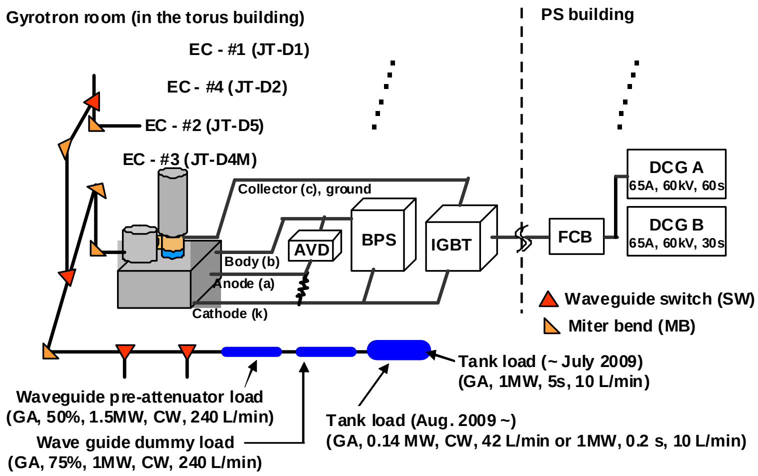

FIG. 1. Schematic view of the JT-60 ECRF system for high power and long pulse experiments. The EC-#2 was used for the high power operation and the EC-#3 was used for long pulse operation with improved gyrotron.

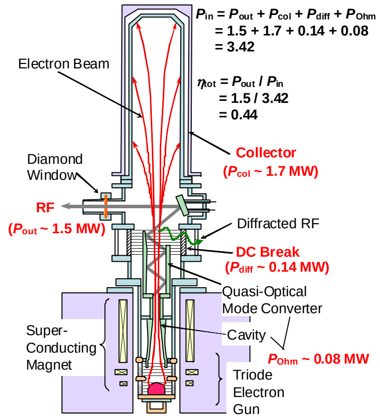

FIG. 2. Structure of the JT-60 gyrotron and an example of the heat load for an output power of 1.5 MW of a gyrotron.

2. High power operation of a JT-60 gyrotron

The collector of a gyrotron is heated by the electron beam. As shown in FIG. 2, the power of the electron beam absorbed at the collector (P_{col}) is given by $P_{col} = P_{in} - P_{rf} = P_{out} / \eta_{tot} - P_{diff} - P_{Ohm}$ where P_{in} (= I_{beam} x V_k) is an input power from the main power supply and I_{beam} and V_k are the beam current and the cathode voltage with respect to the ground (collector electrode), respectively. P_{diff} and P_{Ohm} are diffraction and Ohmic loss in the gyrotron depending on the gyrotron design. The η_{tot} is a total efficiency (typically 0.3 ~ 0.5) and it strongly depends on the operation parameters of the gyrotron such as I_{beam}, acceleration voltage V_{beam} (voltage between body and cathode electrodes) and the cavity magnetic field B_c applied by a super-conducting magnet. It is essential to increase η_{tot} by optimizing operation parameters for reducing collector heat load at the fixed P_{out} of 1.5 MW.

In order to extend pulse length at P_{out} = 1.5 MW on the JT-60 gyrotron without overheating of the collector, the P_{col} is to be less than 1.7 MW, which was estimated by the collector temperature measurements on high power and long pulse oscillations in JT-60 [3]. The condition is satisfied by obtaining at the η_{tot} of ~ 45% or higher. Although the η_{tot} of 40 ~ 45% was obtained with pulse lengths of up to 1 s at 1.5 MW [2, 3], the beam current reduction due to cathode cooling caused the reduction of the output power at the pulse length of longer than 1 s. If, however, the beam current was increased to keep output power of 1.5 MW for long pulse, the η_{tot} was less than 40% so far resulting in $P_{col} > 2.1$ MW. Simultaneous realization of an output power of 1.5 MW and an efficiency of 45% had not been achieved. Since the reduction of the heat load by > 20% was required for long pulse operation at 1.5 MW, we developed a new operation technique for increasing total efficiency.

2.1. Development of an operation technique for high efficiency oscillation

The JT-60 ECRF system is featured by employing the 110 GHz gyrotron with a triode type magnetron injection gun (MIG) which is shown in FIG. 3. One of the advantages of the triode MIG compared with a diode type MIG is that the pitch factor of the electron beam can be changed during an oscillation by changing the ratio of V_{ak} to V_{ab} independently of V_{beam}. Here, V_{ak} and V_{ab} are the voltage between anode and cathode electrodes and the voltage between anode and body electrodes. The pitch factor of the electron beam strongly affects the oscillation condition [4]. In the JT-60 ECRF system, the V_{ab} can be actively controlled during oscillation by the Anode Voltage Divider (AVD) with a response time of the order of 10 ms for pre-programmed control and the order of 0.01 ms for quick modulation [1, 3].

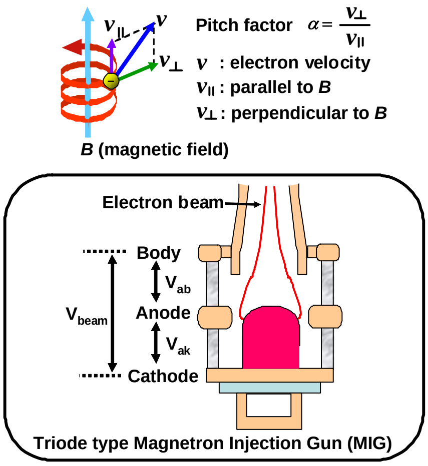

FIG. 3. Schematic view of a triode type magnetron injection gun and the definition of the pitch factor.

Generally, the oscillation efficiency is higher at the lower B_c while higher pitch factor is required at lower B_c (if other parameters are fixed) to satisfy the start-up condition of the oscillation: the region that satisfies the start-up condition is so called soft-excitation region. However, the higher pitch factor usually causes trapped electrons between the mirror magnetic field and the potential of the electron gun. The trapped electrons appear as a leakage current I_a to the anode electrode. The I_a should be minimized to avoid the trouble of the electron gun and to avoid undesired changing in the oscillation condition for long pulse operation.

In order to solve the issue of the increase of I_a at high efficiency (low B_c) region for long pulse operations, we developed a new operation technique. Figure 4 shows the typical time evolutions of the RF signal with the applied voltages and beam current for (a) the conventional operation without active control of V_{ak} and (b) the new operation technique with active control of V_{ak}, respectively, where operation parameters were the same for both operations except the V_{ak} at the beginning of the pulses (t < 80 ms). The target V_{ak} was set at lower value of ~ 40 kV where the I_a was acceptable (< 15 mA). The B_c was set at lower value of 4.395 T. Since the B_c was lower than the lowest B_c which satisfies the start-up condition, the target mode ($TE_{22,6}$ mode) could not be excited by the conventional operation. In this case undesired neighboring mode of $TE_{21,6}$ was excited instead of the target mode. In the new technique, V_{ak} was set higher by ~ 1.5 kV to excite the target mode by increasing the pitch factor at the beginning of the pulse. The oscillation of the target mode appeared at t ~ 50 ms,

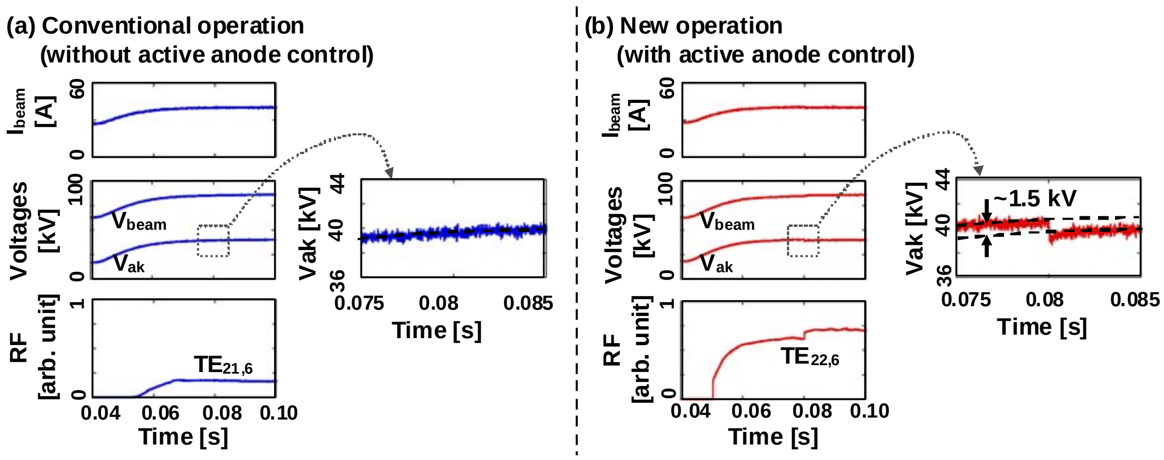

FIG. 4. Typical waveforms of (a) conventional operation and (b) new operation technique. All operation parameters were fixed except the small difference in the V_{ak} at the beginning of the pulse. The start up condition of the target mode of $TE_{22,6}$ is satisfied by increasing V_{ak} by ~ 1.5 kV. Once the target mode excited, the target mode is maintained even the V_{ak} was reduced at t = 80 ms.

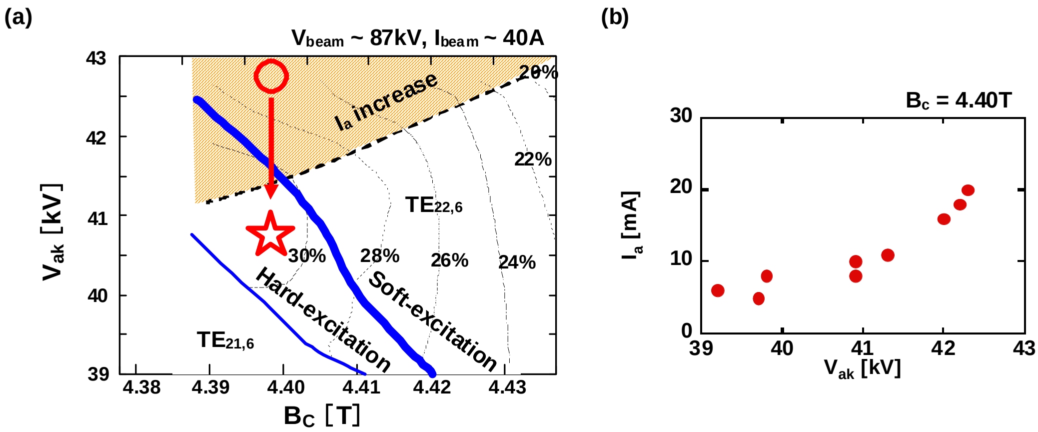

FIG. 5. (a) Contour of the oscillation efficiency, $\eta_{osc} = P_{out} / (V_{bk} \times I_{beam})$, at I_{beam} ~ 40 A and V_{bk} ~ 87 kV and (b) the V_{ak} dependence of the anode leakage current, I_a, at B_c = 4.40 T. The efficiency was evaluated only by oscillations with the pulse length of 1 s. The V_{ak} was evaluated at the end of the pulse which saturated at t ~ 0.1 s. In hatched area, increase of trapped electrons caused the increase of the anode leakage current for long pulse. An example of the pass (the arrow from the circle to the star) of the new operation technique that allows an operation in the hard-excitation region is shown.

since the oscillation condition was satisfied and grew with an increasing of the voltages. When the power increased to the nominal level at t = 80 ms, V_{ak} was decreased by ~ 1.5 kV to reduce the I_a for long pulse operation. Although final operating parameters were the same as those of the conventional operation, the oscillation at the target mode was maintained, rather the RF signal increased. It is noted that the target mode was able to be maintained by changing the anode voltage any time of t > 50 ms as well as t = 80 ms. These experimental results clearly indicate that the oscillation with the new technique was in the so-called hard-excitation region, where the oscillation cannot be excited from the small oscillation amplitude of noise level but once the oscillation is established the high efficiency operation is possible [5]. In this technique, the high efficiency is expected by operating at the lower B_c while the I_a is able to be kept low during the whole pulse except the initial of the pulse by operating at the lower V_{ak}.

In order to demonstrate effectiveness of this operation technique for increasing oscillation efficiency, $\eta_{osc} = P_{out} / (V_{bk} \times I_{beam})$, we obtained the oscillation efficiency by changing B_c and V_{ak} at the fixed I_{beam} ~ 40 A and V_{bk} ~ 87 kV with pulse length of 1 s as shown in FIG. 5 (a). The V_{ak} dependence of the I_a at B_c ~ 4.40 T is also shown in FIG. 5 (b). In these operation parameters, the oscillation efficiency was less than 30% by conventional operation in the soft-excitation region while the higher efficiency of > 30% was obtained by new technique operating in the hard-excitation region. At the highest oscillation efficiency (B_c = 4.39 T and V_{ak} = 41.0 kV) the anode leakage current was low, I_a~ 10 mA, since the operation was available at lower V_{ak}. In this way, we successfully extended the operation region to the hard-excitation region.

Although the main purpose of development of this technique was to demonstrate an oscillation of 1.5 MW with efficiency of ~ 45% in this case, the technique itself is applicable for obtaining high efficiency by operating in the hard-excitation region independently of the output power and the frequency of the gyrotron if the triode type MIG is equipped. The advantage of this technique is to enable a quick access to the hard-excitation region, which is effective when the quick and high power RF injection is required such as for the application to the neoclassical tearing mode stabilization [6].

2.2. Achievement of an oscillation of 1.5 MW for 4 s

By applying the new operation technique at the beam current of ~ 60 A, the longest pulse length of 4 sec was obtained at the time averaged output power of 1.5 MW which is the world record of the power on the long pulse gyrotron [7]. Figure 6 shows the temporal evolution of the applied voltages, beam current, RF signal detected by a diode detector, which was installed to a miter-bend in the transmission line, and the temperature rise of the cooling water for the pre-attenuator load. The I_{beam} was slightly decreased from 60 A to 56 A due to cathode cooling. On the other hand, the RF signal was almost constant at t > 0.5 s, rather increasing slightly at t > 1 s which might be due to slightly higher oscillation efficiency at 56 A than that at 60A. The output energy of the gyrotron was evaluated by the temperature rise of the cooling water of the pre-attenuator load (the transmission efficiency of 87% including MOU and the absorption rate of 50% were taken into account). The evaluated gyrotron output energy and the pulse length obtained with same operation parameter are shown in FIG. 7 and it clearly shows the output power was constant at 1.5 MW. The total efficiency at t = 4 s was about 45% that was the target efficiency. As shown in FIG. 8, we successfully expanded the operation region from 1 MW to 1.5MW with a pulse length of longer than 1 s. Since the time constant of the cavity expansion, space charge neutralization and the collector heat load is around 1 s, the demonstration of robust operation with pulse length of 4 s gave us good prospect for further pulse length extension.

Figure 9 shows (a) the spatial profile (in height) of the collector temperature measured with thermocouples installed on the right hand side of the collector (by seeing the output window

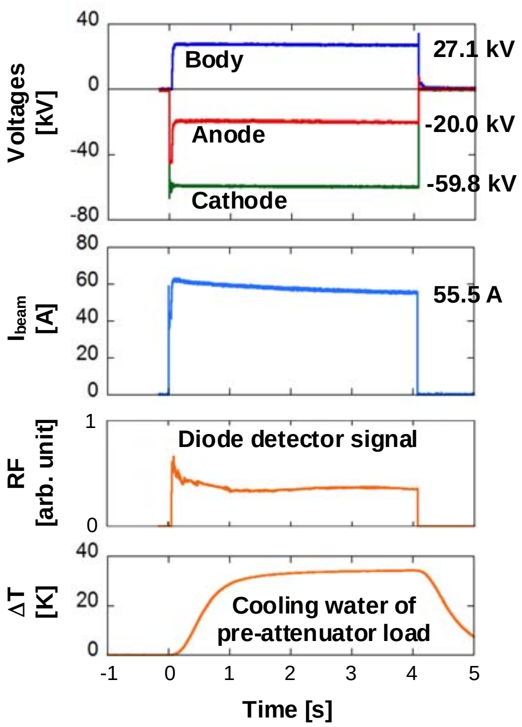

FIG. 6. Temporal evolutions of the applied voltages, beam current, RF signal detected by a diode detector at the miter bend and temperature rise of the cooling water for the pre-attenuator dummy load on the oscillation of 1.5 MW for 4 s.

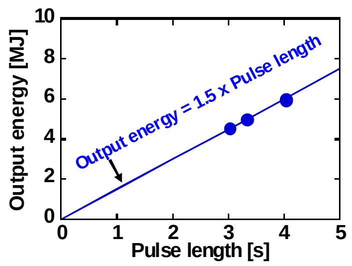

FIG. 7. Output energy of the gyrotron and pulse length. Straight line shows the expected energy at the output power of 1.5 MW.

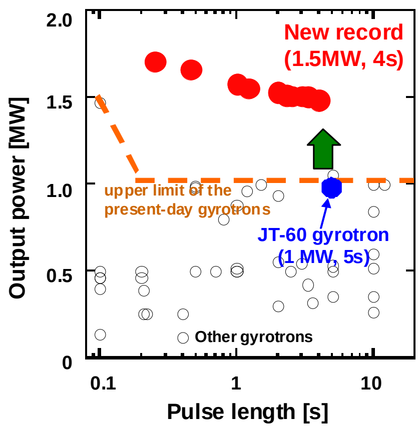

FIG. 8. Progress on the high power gyrotron oscillation achieved by the JT-60 gyrotron (closed circles) and other gyrotrons (open circles) in the world (before 2008).

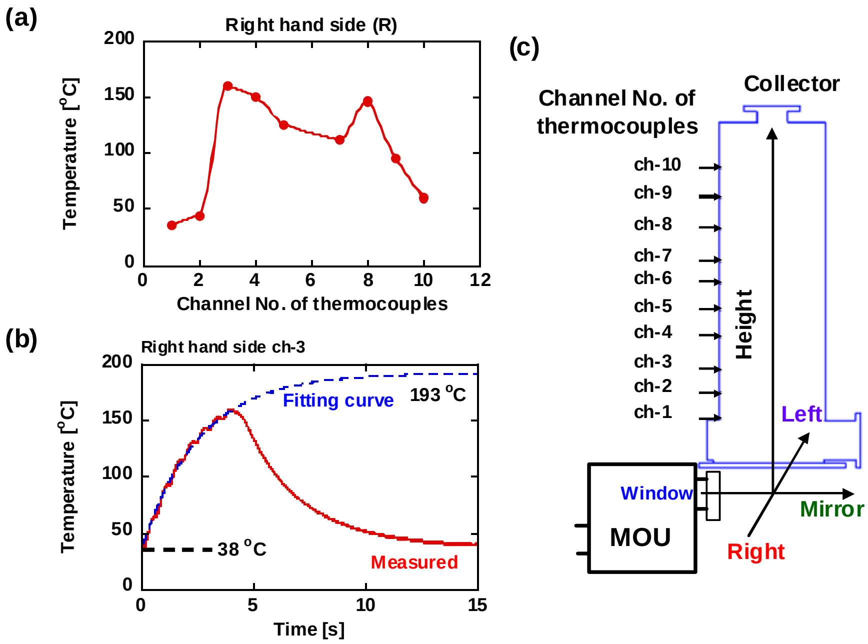

FIG. 9. (a) Spatial distribution of the collector temperature at the right hand side of the collector (seeing from the MOU side) measured with thermocouples installed at the middle of the inner and cooled surfaces of the collector in depth and (b) the time evolution at ch-3 of an oscillation at 1.5 MW for 4 s. The position of the thermocouples, ch-1 ~ ch-10, are also shown in (c).

from the MOU side) and (b) the temporal evolution of one of the thermocouples, which gave the highest temperature in FIG. 9 (a). The temperature before the oscillation was about 38 °C. It is noted that the temperature of the primary cooling water of the ECRF system, which was 20 °C in JT-60 experiment, was 35 ~ 40 °C in this experiment, since the secondary cooling water system was not operated. The electron beam was swept on the collector surface by sweeping the collector sweeping coil current at the frequency of ~ 1.7 Hz. The pulse length of 4 s was enough for evaluation of the temporal behavior of the temperature rise and the temperature rise reached to 80% of its maximum at t = 4 s. It is estimated that the temperature rise by this oscillation condition reaches to the maximum of ~ 160 °C at ~ 10 s that is acceptable for longer pulse. Moreover we found that the temperature distribution was not completely uniform in both axial and azimutual directions. Therefore, we will modify the waveform of the sweeping coil which has triangle waveform in this case, and it will result in further reduction of the peak temperature which is also good for reducing repetitive stress.

The pulse length of 4 s was limited by the stray radiation, which caused overheating at the cooling water for the DCB between the collector and body electrodes. Figure 10 shows the temperature rises of the cooling water at the collector (900 L/min), cavity (85 L/min), sub-window (3 L/min) and the DCB, which consists of two lines of inner (13 L/min) and outer (9 L/min). The temperature before oscillation was 20 °C for the DCB (outer) and 38 °C for others. The temperature of the DCB cooling water was increased much and the water temperature of the DCB (inner) exceeded 100 °C that was higher than the operation limit of the cooling system. Therefore, the remaining issue for high power long pulse oscillation is to reduce the stray

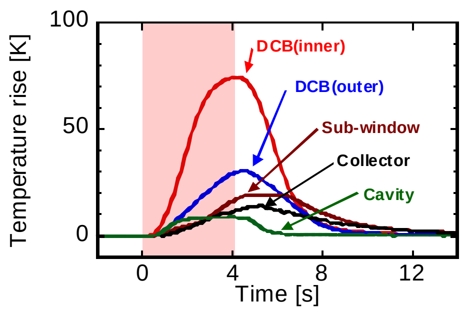

FIG. 10. Temporal evolution of temperature rise of the coolant water for the dc-break (inner and outer), sub-window, collector and cavity.

radiation.

3. Long pulse ECRF system development

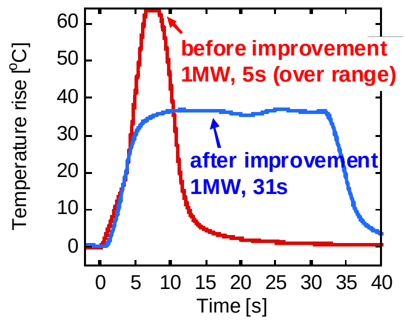

FIG. 11. Temporal evolution of the coolant water for the DC-break before and after improvement of the mode convertor.

We modified the JT-60 ECRF system such as power supply, transmission and control systems, to expand its pulse duration from 5 s to 50 s at the beam current of 65 A in order to study the long pulse capability of the system. This modification will be continued toward 100 s operation for JT-60SA. For instance, the DC Generator (DCG) for the main power supply (65A, 60 kV, 30 s) was replaced with DCG-A (65A, 60 kV, 60 s) which was previously used for the lower hybrid-A system in JT-60. The large tank load (General Atomics (GA), 1 MW, 5s) as the terminate of the transmission line was replaced with a small tank load (GA, 0.15 MW, Continuous Wave (CW)) at the water flow rate of 42 L/min which was previously used as a short pulse load (1MW, 0.2 s) at water flow rate of 10 L/min. The modified dummy load system is expected to be used at 1 MW, CW, and it enables to measure output power without assumption of the absorption rate of the pre-attenuator load.

The most significant modification is an improvement of the mode convertor in the gyrotron for reducing diffraction loss in the gyrotron. As mentioned above, the DCB that is installed between body and collector electrodes for gyrotrons utilizing a collector potential depression technology is significantly heated by the stray radiation. Recent development of the internal mode convertors [8, 9] enables to reduce the diffraction loss to typically 2 ~ 4% from 8 ~ 10% of old type (single helix) mode convertors and it was a key to achieve long pulse operation [5]. To apply this new mode convertor to the JT-60 gyrotron, we re-designed the mode convertor and the diffraction loss was improved from 6.8% to 3.5% in calculation. Then, a new gyrotron was fabricated for confirming the effectiveness of the improvement toward long pulse operation in JT-60SA. It was found that the stray radiation measured at the DCB cooling water was reduced by half as shown in FIG. 11. The detailed evaluation on the power balance in the gyrotron showed that the diffraction loss was reduced from 9% to 3% in the experiment. Consequently solutions for the recognized major issues at present for expanding the pulse length of the gyrotron oscillation were found.

Since the transmission line on the JT-60 ECRF system was designed for achieving 1 MW for 5s, active cooling of the waveguides was not sufficient for long pulse operation. The waveguides near miter-bends were strongly heated due to mode conversion. The high power experiment showed that the temperature rise of the waveguide were 5 ~ 15 °C depending of the distance from the miter-bend with a gyrotron output power of 0.45 MW for 10 s [10]. These correspond to the temperature rises of 110 ~ 330 °C for an oscillation of 1 MW for 100 s, when adiabatic condition is assumed. Such high temperature is unacceptable for the waveguides made of aluminum even the heat transfer to air and support of the waveguides is taken into account. Moreover, temperature is not completely decreased to its initial value after each oscillation with a duty cycle of ~ 1/100 without active cooling on the waveguides and it was not desired for repeated operations at the pulse length of longer than 10 s. Therefore we introduced two kinds of cooling attachments (one is a cupper plate with brazed water pipe which surrounded the waveguide and the other is a waveguide coupling made of aluminum which has two straight water lines inside the body) into the waveguides. It was found at present effective for avoiding increase of the initial temperature of each oscillation.

By employing these progresses, the pulse length exceeded 30 s at 1 MW with the total efficiency of higher than 40% with no overheat in the gyrotron. For the pulse length longer than 20 s, pre-programmed heater current control and anode voltage control, which have been developed and demonstrated in the JT-60 ECRF system [1], were applied for sustaining the oscillation and output power. It was confirmed that the beam current, which was ~ 45 A at the initial of the pulse and decreased due to cathode cooling, became constant (~ 38 A) at *t* ~ 30 s. Consequently, the oscillation condition is expected to be satisfied for longer pulse. Further extension of the pulse length is continued toward 100 s by improving the transmission line using waveguides with a diameter of 60.3 mm which was newly designed and developed for JT-60SA.

4. Summary

The development of high power and long pulse ECRF system has been performed in JT-60. Remarkable progress was made on high power operation of the JT-60 gyrotron by developing a new operation technique that results in achievement of an oscillation of 1.5 MW for 4 s with an efficiency of ~ 45%, for the first time.

The improvements of the JT-60 ECRF system have been made toward 100 s oscillation at 1 MW. The remarkable reduction of the diffraction loss in the gyrotron was confirmed using newly fabricated gyrotron. The conditioning operation has been carried out and the tentative pulse length exceeded 30 s at 1 MW. The pulse length extension will be continued by improving the transmission line.

These progresses significantly contribute to enhancing the high power and long pulse capability of the ECRF system toward JT-60SA.

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