Recent Results from the Development of the Electron Cyclotron Heating System for JT-60SA toward High-Power Long-Pulse Operations*)

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Development of an electron cyclotron (EC) wave system was conducted in an effort to achieve the capability required in JT-60SA. Pulse duration at 1 MW output was extended to 31 s. Transmission line components with a diameter of 60.3 mm were installed in 2011 to reduce temperature rise during a gyrotron oscillation. Development of a dual-frequency gyrotron was started to enable heating and current drive in the core region of the JT-60SA plasma for the toroidal field of 2.3 T. The EC wave frequency was chosen to be 138 GHz to meet the requirements of physics experiments and gyrotron design. Fabrication of the gyrotron began in 2011.

Keywords: electron cyclotron wave, ECH, ECCD, gyrotron, waveguide, JT-60SA

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1. Introduction

Electron cyclotron (EC) waves are widely used in tokamaks for many purposes such as electron heating, current drive, and instability control because of their capability for a highly localized deposition profile. In addition, EC waves can be used to assist plasma initiation and to clean the first wall. In JT-60SA, an EC wave system will be installed and used for these purposes. Although the system for JT-60U is reused as much as possible, modifications and developments of almost all components such as power supplies, gyrotrons, transmission lines, antennas, and control systems are required, because the specifications for JT-60SA are much higher than those for JT-60U. This paper describes recent results from the development of the EC wave system for JT-60SA, particularly focusing on the development of high-power long-pulse gyrotrons and their performance. First, the specifications of the EC wave system are described in Sec. 2. Progress in the pulse duration and output power of the gyrotrons is described in Sec. 3. Performance of electron cyclotron heating (ECH) and electron cyclotron current drive (ECCD) in one of the baseline scenarios is described in Sec. 4. Development of a dual-frequency gyrotron is described in Sec. 5. Finally, the study is summarized in Sec. 6.

2. Specifications of EC Wave System

A schematic view of the EC wave system is shown in Fig. 1. The gyrotrons are installed in the gyrotron room outside the torus hall. EC waves generated by the gyrotrons are transmitted by waveguides with a diameter of 31.75 mm or 60.3 mm. A transmission line, typically 80 m in total length, is connected to the launchers located at the upper oblique ports in the P-1, P-4, P-8, and P-11 sections. Each of the EC wave ports contains two or three transmission lines and a "linear motion" launcher [1], as shown

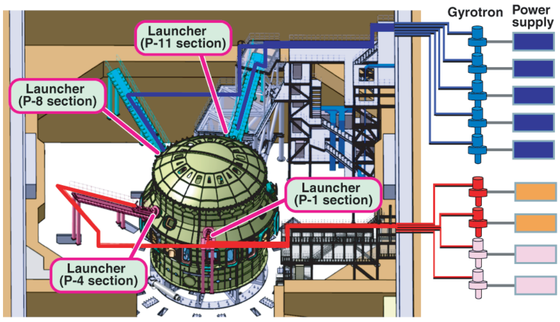

Fig. 1 Schematics of the power supplies, gyrotrons, transmission lines, and launchers in the gyrotron room and torus hall. Components shown in red will be fabricated by JAEA for the Initial Research Phase. Components shown in pink will be improved for the Integrated Research Phase. Components shown in orange will be fabricated by EU. Components shown in blue will be fabricated for the Integrated Research Phase.

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in Fig. 2. This launcher has an advantage in that flexible parts of the cooling water pipes to enable a change in the injection angle located outside the JT-60SA vacuum vessel. This structure would reduce the risk of water leakage inside the vacuum vessel. While the transmission lines of each port share one of the reflection mirrors ("Mirror 2" in Fig. 2), the directions of the EC waves from each transmission line can be changed independently. Details of the development of the linear-motion antenna are described elsewhere [2, 3].

The EC wave system is upgraded according to the progress made in the three research phases: the Initial Research Phase, the Integrated Research Phase and the Extended Research Phase. Injection power to the plasma and the pulse duration in these research phases are shown in Table 1. Output power of all these gyrotrons is typically 1 MW, and the frequency of the output millimeter wave is 110 GHz. (Additional frequency is under consideration as described later.) In the Initial Research Phase, two of the four gyrotrons including the power supply are the ones used in JT-60U. The pulse duration and duty cycle are 5 s and 1/60, respectively. The other two gyrotrons, whose pulse duration and duty cycle are 100 s and 1/18 (which enables 100 s injection after 1800 s break) are newly fabricated. The power supply is procured by EU. In the Integrated Research Phase, the number of gyrotrons is increased to nine, and their duration and duty cycle are 100 s and 1/18. All the gyrotrons have the capability of power modulation at >5 kHz from the Initial Research Phase for stabilization of neoclassical tearing modes (NTMs).

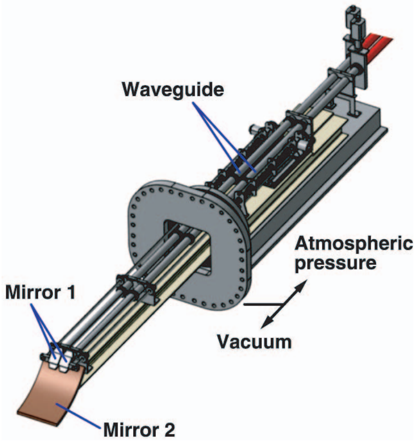

Fig. 2 Schematic drawing of the linear-motion launcher.

Table 1 Injection power and duration in each research phase.

Research phase	Number of gyrotrons	Injection power & duration
Initial	4	1.5 MW, 5 s 1.5 MW, 100 s
Integrated	9	7 MW, 100 s
Extended		

3. Extension of Output Power and Pulse Duration

Gyrotron operations toward the target values of JT-60SA gyrotrons have continued since the completion of JT-60U experiments in August 2008. Issues to be resolved exist both in the gyrotrons and transmission lines. During the operations for JT-60U experiments, a temperature increase in the cooling water at the DC break between the collector and the body of the gyrotron exceeded about 65°C because of stray radiofrequency (RF) waves (Fig. 3). To decrease the temperature, a new mode converter was designed and installed. As a result of conditioning operations, the pulse duration was successfully extended to 17 s in 2009 and to 31 s in 2010 at an output power of 1 MW (Fig. 4). The temperature of the cooling water reached a steady state in about 10 s, and the temperature increase was less than 40°C. The duration was limited by an increase in the surface temperature of the transmission line during the gyrotron oscillation. Thus, it was concluded that issues originating from the gyrotron have been overcome at least within this pulse length, and that further extension is

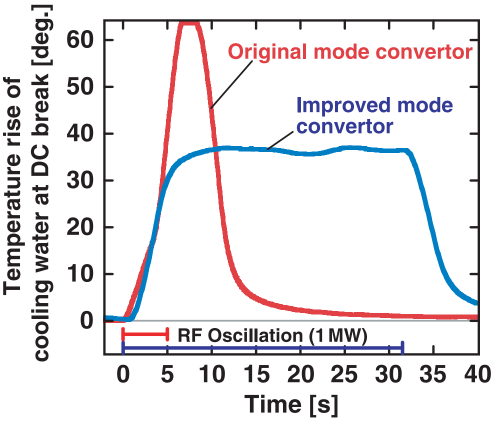

Fig. 3 Temporal evolution of the cooling water temperature at the DC break for 1 MW output.

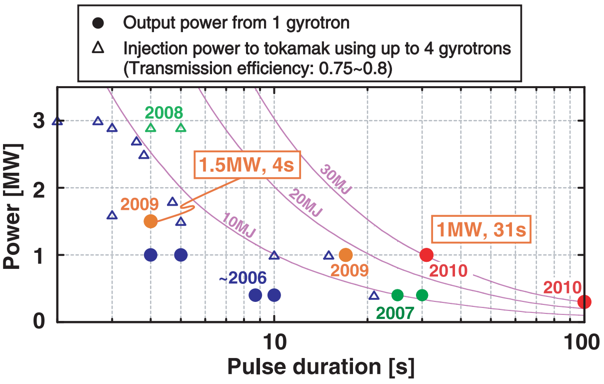

Fig. 4 Progress in the pulse duration and power. The closed circles indicate the output power from one gyrotron, and the open triangles indicate the injected power to JT-60U plasmas using up to four gyrotrons.

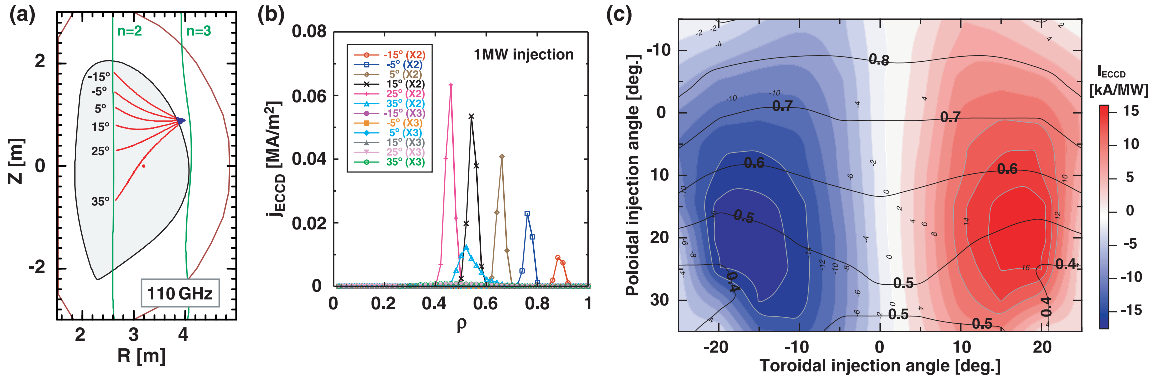

Fig. 5 ECCD characteristics of 110 GHz EC wave in Scenario 5. (a) Ray trajectories for different poloidal injection angles, (b) profiles of EC-driven current for different poloidal injection angles, (c) a contour plot of the total EC-driven current. In (a) and (b), the toroidal injection angle is set at 15°. The starting point of each ray in (a) roughly corresponds to the center of the aperture of the stabilization plate. The black contour lines in (c) indicate the peak position of ECCD profiles.

possible by reducing the outgas from the components both inside the gyrotron and transmission line through continuous operations. In addition to extending the duration at 1 MW output, operations to obtain an output power exceeding 1 MW were performed, and an output power of 1.5 MW was sustained for 4 s by using a gyrotron without an improved mode converter [4]. Operations to extend the pulse duration are planned by using the above upgraded gyrotron.

In the course of long-pulse operations without cooling, the temperature on the surface of the transmission line continuously increased; the temperature reached about 50–70°C for a 1 MW, 15 s output. To suppress such a temperature increase, whose typical time constant is on the order of 100 s, the straight section of the transmission line was covered with copper plates with water pipes. The effectiveness was confirmed in a 99 s operation at 0.3 MW. In order to achieve longer pulse duration by reduction in (a) the power density in the transmission line and (b) the mode conversion loss at miter bends, 60.3 mm diameter transmission components were installed in place of the previous 31.75 mm diameter components. After the Great East Japan Earthquake, the whole gyrotron system was inspected in detail and minor damages were fixed. Operations were resumed in May and are progressing steadily.

4. Performance of Heating and Current Drive

The frequency of the EC waves is assumed to be 110 GHz in order to fully utilize the gyrotron system for JT-60U. Figure 5 shows the ECCD characteristics evaluated by the EC-Hamamatsu code [5] for Scenario 5, which aims at steady-state sustainment of a high-beta plasma with negative central magnetic shear [6]. Typical plasma parameters in this scenario are as follows: plasma current I_p = 2.3 MA, toroidal field B_t = 1.7 T, safety factor at 95% flux surface q_{95} = 5.7, central electron temperature $T_e(0)$ = 5.85 keV and central electron density $n_e(0) = 6.8 \times 10^{19}$ m^{-3}. The range of the poloidal injection angle θ_p is −15° to 40°, where the negative value indicates the direction above the horizontal plane. The range of the toroidal injection angle θ_t is set at −15° to +15°, which is under discussion to meet physics requirements. Here, the plus and minus signs indicate ECCD in the co-direction (the same direction as the plasma current) and the counter-direction, respectively. The half width of the full beam divergence is set at 2°.

In this condition, EC waves are fully absorbed only near the resonance layer of the second harmonic resonance. This results in narrow ECH/ECCD profiles, which are suitable for NTM stabilization. The full width at half maximum (FWHM) of the ECCD profile is typically 0.04 in units of normalized minor radius. The ratio of the EC-driven current density j_{EC} to the bootstrap current density j_{BS} is 0.27–0.20 at ρ = 0.45–0.8 for 1 MW injection. This indicates that the value of j_{EC}/j_{BS} reaches unity for the EC wave power of 4–6 MW by which effective current profile tailoring is expected. Reliable NTM stabilization is also expected (Note that complete NTM stabilization at $j_{EC}/j_{BS} < 1$ was achieved in JT-60U by detailed adjustment of the ECCD location [7].).

The ECCD location ranges from $\rho \sim 0.45$ to 0.9, as shown in Figs. 5 (b) and 5 (c). This will cover the region of an internal transport barrier in most cases. However if ECH/ECCD in the more central region (e.g., $\rho \lesssim 0.3$) is desired, an increase in the toroidal field needs to be considered: toroidal fields of 1.8 and 2.0 T enable ECCD at $\rho \sim 0.2$ and 0.1, respectively.

The amount of non-inductively driven current in the off-axis region is an important parameter in Scenario 5 in order to sustain a reversed shear plasma. In particular, ECCD plays an important role in current profile tailoring by utilizing its capability of localized current drive. EC-Hamamatsu code calculations show that the maximum EC-driven current in the co-direction and the counter-direction is obtained for the toroidal injection angle of ~15° and

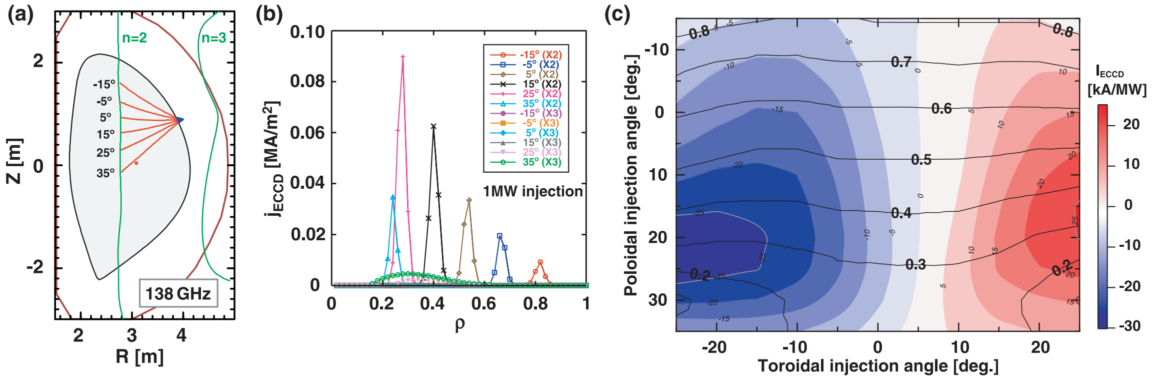

Fig. 6 ECCD characteristics of 138 GHz EC wave in Scenario 2. (a) Ray trajectories for different poloidal injection angles, (b) profiles of EC-driven current for different poloidal injection angles, (c) a contour plot of the total EC-driven current. In (a) and (b), the toroidal injection angle is set at 15°. The starting point of each ray in (a) roughly corresponds to the center of the aperture of the stabilization plate. The black contour lines in (c) indicate the peak position of ECCD profiles.

$\sim -15°$, respectively. As shown in Fig. 5 (c), in this configuration, the amount of EC-driven current is symmetric with respect to $\theta_t = 0°$. Thus, nearly the maximum EC-driven current in Scenario 5 is obtained under the present range of the toroidal injection angle.

5. Development of Dual-Frequency Gyrotron

The maximum toroidal field at the plasma center in JT-60SA is 2.3 T, and baseline scenarios at this toroidal field are naturally considered. In such configurations, 110 GHz EC waves are deposited only in the peripheral region: EC-Hamamatsu code calculations show that the innermost location is $\rho \sim 0.7$ even for $\theta_t = 0°$. (This means that the 110 GHz EC waves are useful for edge ECH/ECCD, e.g., for control of edge localized modes.)

To enable ECH/ECCD in the core plasma region at $B_t \sim 2.3$ T without losing the capability of the 110 GHz EC wave, development of a dual-frequency gyrotron was started. As a result of ECH/ECCD calculations at $B_t \sim 2.3$ T, an EC wave frequency of 130–140 GHz was found to be suitable for deposition in the central plasma region. Some restrictions are arising from the gyrotron design. Oscillation modes obtained with similar beam radii need to be chosen to use the same magnetron injection gun and superconducting magnet. In addition, the beam angle at the radiator exit of the mode converter needs to be similar to each other to reduce the diffraction loss. Furthermore, a diamond vacuum window whose thickness is close to an integer times half wavelength needs to be chosen to reduce the reflection of the output beam. As a result of detailed investigations, the frequency combination was chosen to be 110 GHz and 138 GHz with the mode numbers of $TE_{22,8}$ and $TE_{27,10}$, respectively. The thickness of the diamond window was chosen to be 2.3 mm, which corresponds to 4 and 5 times the half wavelength of 110 GHz and 138 GHz electromagnetic waves in the diamond window, respectively.

ECCD characteristics using 138 GHz EC waves in Scenario 2 are shown in Fig. 6. Scenario 2 aims at full-I_p operations with a single-null divertor and full injection power (41 MW) [6]. Typical plasma parameters are as follows: $I_p = 5.5$ MA, $B_t = 2.3$ T, safety factor at 95% flux surface $q_{95} = 3.0$, $T_e(0) = 13.5$ keV, and $n_e(0) = 7.7 \times 10^{19}$ m^{-3}. The calculation results shown in Fig. 6 indicate that ECCD in the region $\rho = 0.25$-0.8 is possible at this frequency. The range covers the region where NTMs with $m/n = 3/2$ and $2/1$ are expected to appear. Here, m and n are the poloidal and toroidal mode numbers, respectively. Note that the peak EC-driven current density is low for $\theta_p = 35°$. This is because the EC waves are absorbed well before reaching the second harmonic resonance layer because of the third harmonic resonance (see Fig. 6 (b)). Although such third harmonic absorption is also seen for $\theta_p = 25°$, the magnitude is not large and a sharp profile owing to second harmonic absorption is obtained. The amount of the third harmonic absorption depends on electron temperature. In fact, for example, when $T_e(0) = 5$ keV, such third harmonic absorption is negligibly small, and a sharp ECCD profile is obtained even for $\theta_p = 35°$. The contour plot of the total EC-driven current shown in Fig. 6 (c) indicates that the total driven current is symmetrical with respect to $\theta_t \sim 5°$. Since the result is different from that in Fig. 5 (c), the range of the toroidal injection angle, which is about 30° in total in the present design, needs to be determined by taking into account physics requirements within the structural limitations of the size of the launcher port and the aperture size of the stabilization plate (e.g., $-10°$ to $20°$).

A design study for the dual-frequency gyrotron was completed, and fabrication was initiated. In addition, the fabrication of a superconducting magnet enabling higher magnetic field and the modification of the gyrotron control system were also initiated. The components will be installed in March 2012.

6. Summary

Steady progress has been made in the development of the EC wave system for JT-60SA toward its target. Gyrotron operations have continued, and the pulse duration at 1 MW output was extended to 31 s after the installation of an improved mode converter. Saturation of temperatures of the gyrotron components suggests that further extension of the pulse duration is possible from the gyrotron side. However, continuous increase in the surface temperature of the transmission line indicates that improvements in the transmission line are needed to sustain the temperature at an acceptable level. A transmission line with a diameter of 60.3 mm was installed to further extend the pulse duration. Operations were resumed in May 2011 after mending minor damages caused by the Great East Japan Earthquake.

Calculations of ECH/ECCD properties indicate that localized ECH/ECCD at $\rho = 0.45$–0.9 is possible in Scenario 5 ($B_t = 1.7$ T) using 110 GHz EC waves. The value of j_{EC}/j_{BS} reaches unity for 4–6 MW injection.

The development of a dual-frequency gyrotron was initiated for ECH/ECCD in the central plasma region in high-B_t discharges. The second frequency was chosen to be 138 GHz from the viewpoints of physics requirements and gyrotron design. Calculations show that ECH/ECCD at $\rho = 0.25$–0.8 is possible in Scenario 2 ($B_t = 2.25$ T). The new gyrotron will be installed in March 2012.

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