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Development of a dual frequency (110/138 GHz) gyrotron for JT-60SA and its extension to an oscillation at 82 GHz

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Abstract. A dual-frequency gyrotron, which can generate 110 GHz and 138 GHz waves independently, is being developed in JAEA to enable electron cyclotron heating (ECH) and current drive (ECCD) in a wider range of plasma discharge conditions of JT-60SA. Conditioning operation of the gyrotron toward 1 MW for 100 s, which is the target output power and pulse length for JT-60SA, is in progress without significant problems. Oscillations of 1 MW for 10 s and 0.5 MW for 198 s were obtained, so far, at both frequencies. Cooling water temperatures in the gyrotron and matching optics unit were saturated in the 198 s oscillation, and the observed maximum water temperature is sufficiently low. In addition to the above activity on the dual-frequency gyrotron development, an oscillation (0.3 MW for 20 ms) at 82 GHz was demonstrated as an additional frequency of the dual-frequency gyrotron. A possibility of the use of fundamental harmonic wave at 82 GHz in JT-60SA has been shown.

1 Introduction

A gyrotron is recognized as a unique high-power millimetre wave source for electron cyclotron heating (ECH) and current drive (ECCD) in magnetically confined fusion plasma experiments. In the early 2000s from the late 1990s, high-power (~ 1 MW) oscillations at the millimetre wave frequencies above 100 GHz were realized by some individually developed gyrotrons in Japan, EU, Russia and US [1]. These gyrotrons were used in some tokamak devices such as JT-60U [2], DIII-D [3] and ASDEX-U [4]. Recently, long-pulse oscillations of several hundreds of seconds at an output power of 1 MW have been demonstrated at the frequencies of 140 GHz for W7-X [5] and 170 GHz for ITER [6, 7]. At the lower frequencies, where diffraction loss in the gyrotron tends to be larger than that at the higher frequencies due to increase in a diffraction effect, long-pulse gyrotrons are under development [8-10]. In addition to developments for realizing higher power and longer pulse, developments for realizing multi-frequency oscillations are in progress since an application of multi-frequency gyrotron gives a flexibility of the ECH/ECCD system for wider experimental conditions without significant increase in a construction cost. In ASDEX-U, a dual-frequency gyrotron was installed and operated for various experiments with the maximum gyrotron output power of 0.95 MW at 140 GHz and 0.85 MW at 105 GHz for 10 s [1, 4].

Table 1. Main parameters of ECH/ECCD systems in JT-60 and JT-60SA.

Parameters	JT-60U	JT-60SA
Frequency	110 GHz	110 GHz (138 GHz)
Pulse duration	5 s	100 s
Power	4 MW at gyro. 3 MW at plasma	9 MW at gyro. 7 MW at plasma
Output power per gyrotron	1 MW	1 MW
Number of Launcher	2	4
Transmission line	Corrugated WG 31.75 mm dia. ~ 60 m	Corrugated WG 60.3 mm dia. 60 ~ 70 m

In Japan Atomic Energy Agency (JAEA), the JT-60U tokamak is under upgrading to JT-60SA [11] that is a super-conducting tokamak constructed as a joint project of a satellite tokamak project of Broader Approach (BA) and a Japanese national project. In JT-60SA, an ECH/ECCD system [12] will be used by upgrading the existing ECH/ECCD system used for JT-60U [2]. Main parameters of the ECH/ECCD system in both JT-60U and JT-60SA are shown in Table 1. The millimetre wave frequency of 110 GHz will be used in JT-60SA for reusing the existing components as much as possible, and this frequency is useful for ECH/ECCD at the toroidal magnetic field of ~ 1.7 T, e.g. a high-beta scenario of

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JT-60SA (scenario 5) [13]. Recently, an application of a dual-frequency ECH/ECCD system in JT-60SA has been discussed [14] since the frequency of 130 - 140 GHz is useful for ECH/ECCD at the toroidal magnetic field of 2.3 T, which is the maximum toroidal magnetic field in JT-60SA. For this purpose, a development of a dual-frequency gyrotron, which can generate high-power (1 MW) millimeter waves at both 110 GHz and 138 GHz independently, is in progress [8]. The target pulse length is 100 s, which is the maximum plasma discharge duration in JT-60SA. Moreover, a study for realizing an oscillation at 82 GHz as an additional frequency of the dual-frequency gyrotron, which will be effective for ECH wall-cleaning and start-up assist by using fundamental harmonic waves in JT-60SA, was carried out.

In this paper, we describe recent progress in a long-pulse operation of the dual-frequency gyrotron and an initial experimental result of 82 GHz oscillations.

2 Dual-frequency gyrotron

In 2011, a development of a dual-frequency gyrotron (110 GHz and 138 GHz) was started in JAEA. The numerical design is summarized in Ref. [8]. The main parameters optimized for dual-frequency operations are (i) the cavity radius (22.8 mm), (ii) the thickness of the output diamond window (2.29 mm) and (iii) the shape of the built-in mode convertor and internal mirrors. Selection of the operating TE mode and optimization of these parameters are important for high-power long-pulse gyrotrons even for a single frequency oscillation. Although optimization of these parameters for both frequencies is required for the design of a dual-frequency gyrotron, we successfully found the parameters with selecting desired operating modes of $TE_{22,8}$ for 110 GHz and $TE_{27,10}$ for 138 GHz. In calculation, it is expected that an oscillation at 1 MW or higher is obtained with an electron beam current of 40 A at the acceleration voltage of 85 kV and the electron pitch factor of 1.1 at both frequencies. Calculated diffraction loss in the gyrotron is lower than 4%, which is sufficiently low for long-pulse operation at 1 MW.

Fabrication of the dual-frequency gyrotron in Toshiba Electron Tubes & Devices Co., Ltd. was finished in 2012. Conditioning operation and optimization of operating parameters have been carried out toward demonstration of an oscillation of 1 MW for 100 s, which is the target output power and pulse length of this gyrotron at two frequencies.

2.1. Experimental setup

An experimental setup for the gyrotron conditioning is shown in Figure 1. Since the conditioning operation has been carried out by using the existing ECH/ECCD system of JT-60 with minor modifications, there are some limitations on the long-pulse operation.

The main power supply, MPS, (130 A, 60 kV, 10 s, 1/60) originally used for operating 4-Klystrons of the Lower-Hybrid RF system in JT-60 was used for the long-pulse operation of the dual-frequency gyrotron with the reduced current (~ 40A for the gyrotron output power of 1 MW). The body power supply (BPS) and anode voltage divider (AVD) used for the JT-60 gyrotrons were reused. An available number of shots per day is significantly limited by the duty cycle (1/60) of the MPS for long-pulse operation.

Pre-programmed control systems for AVD and heater power supply (P/S) developed in JT-60 [2] were used. The control system for the AVD (originally available up

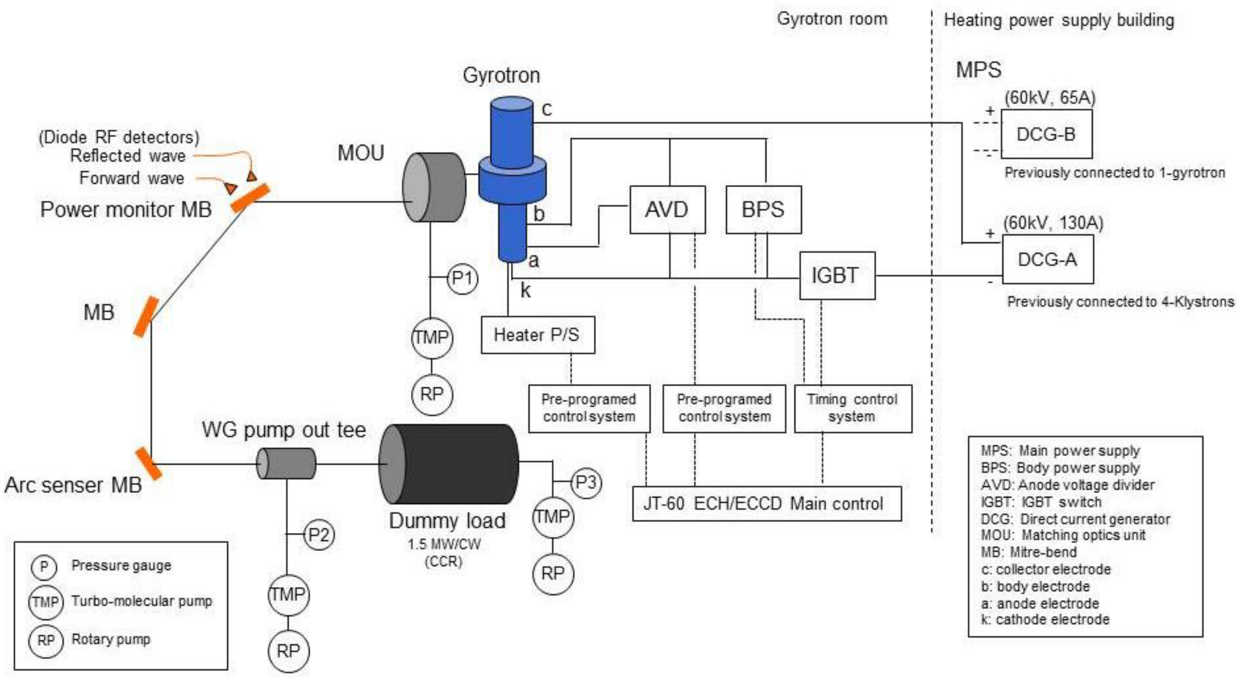

Figure 1. Experimental setup for the conditioning operation of the dual-frequency gyortron.

to 60 s) was modified for maximum duration of 240 s while the control system for the heater P/S (available up to 60 s) was used as it was. The timing control system (originally available up to 99 s) was modified for the maximum duration of 198 s. Thus, operations with well controlled operation parameters are available up to 60 s and the maximum pulse length with limited control of the heater P/S is 198 s. It is noted that the control system will be re-designed and newly fabricated in future for operations of the ECH/ECCD system in JT-60SA.

In the matching optics unit (MOU), phase correcting mirrors optimized only for 110 GHz were installed in this experiment. Thus, the maximum HE_{11} purity will be obtained at only 110 GHz. However, ultra-sonic motors are installed in order to rotate the phase correcting mirrors in both horizontal and vertical directions. Thus it is possible to adjust millimeter wave beam injection angle into the waveguide at the outlet of the MOU without opening the vacuum chamber within few minutes.

Transmission line (TL) using evacuated corrugated waveguides with the diameter of 60.3 mm was connected to the MOU. A dummy load (1.5 MW/CW) developed in Calabazas Creek Research [15] was installed. The total length of the waveguides is approximately 8 m. In addition to the reflected power from the dummy load (<1% in design), large amount of higher order modes might be excited at the waveguide (WG) and WG pump out tee in front of the dummy load since there is a dog-leg configuration with two mitre-bends (MBs). Thus temperature increase in some parts of the WGs is relatively large (approximately 1 °C per 1 MJ of injected power). The WG pump out tee used in early 2013 was designed for short pulses of < 10 MJ since it was designed and tested for a proof of principle of a new diagnostic concept for transmission power profile evaluation [16]. This limited the maximum input energy of the gyrotron operation in early 2013. We added external water cooling of the waveguides and replaced the pump out tee with the one without diagnostic component in September 2013. After this modification, the TL has a capability of 100 MJ as shown in the following section.

2.2 High-power (1 MW) oscillations

The conditioning operation of the dual-frequency gyrotron was carried out in the early 2013 within the limitation of 10 MJ. Operation parameters of acceleration voltage, V_{bk}, anode-cathode voltage, V_{ak}, collector beam current, I_c, and the cavity magnetic field were roughly optimized to obtain reliable oscillations with high efficiency. In August 2013, we obtained oscillations of 1 MW for 10 s at both frequencies, for the first time. Figure 2 shows operation parameters at each frequency. It is noted that the gyrotron developed in JAEA equipped with a triode type magnetron injection gun (MIG). Consequently, it is possible to optimize the electron pitch factor at each frequency by modifying the ratio between V_{ak} and V_{bk}. As seen in Fig. 2, the V_{ak} at 138 GHz is larger than that of the 110 GHz. In this case, the ratios V_{ak}/V_{bk} are 0.46 and 0.52 at 110 GHz and 138 GHz, respectively. The oscillation efficiency (not including an effect of collector potential depression) is ~31% at both frequencies. The total efficiency obtained so far is limited to 43% - 45% due to limitation of the MPS, by which the cathode voltage and body voltage cannot be optimized. By upgrading the MPS in JT-60SA, the higher total efficiency of 50% is expected by operating at the reduced cathode voltage while increasing the body voltage.

In the above oscillations, we did not observe any problems on the gyrotron, and the pulse length of 10 s or energy of 10 MJ was limited by the TL as mentioned above. We evaluated the diffraction loss in the gyrotron and MOU. The gyrotron internal diffraction loss was 3 – 4 % at both frequencies, and it is sufficiently low for long-pulse operation. The diffraction loss in the MOU was around 4% at both frequencies. It should be noted that the phase correcting mirrors are optimized only for 110 GHz, as mentioned above. Thus, the amplitude and phase profile at the inlet of the waveguide is not HE_{11} profile at 138 GHz. However, we confirmed that the low diffraction loss of ~ 4% is obtained at 138 GHz by optimizing the beam injection angle into the waveguide. Moreover, we found that the temperature increase in the TL for an oscillation at 138 GHz is comparable with that at 110 GHz. The evaluation and optimization of the HE_{11} purity in the transmission line is a remaining issue.

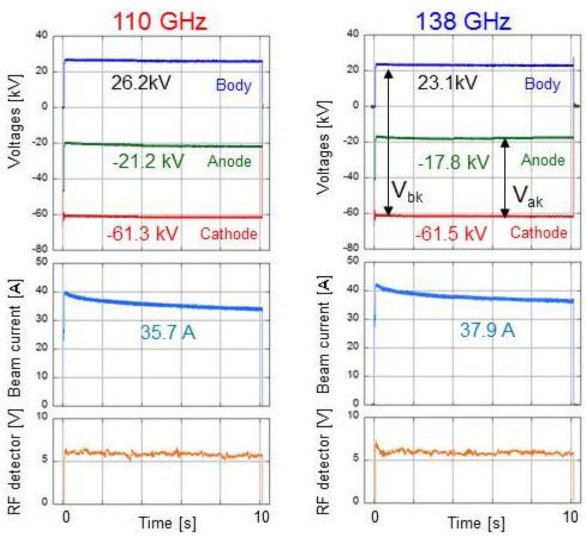

Figure 2. Temporal behaviour of operation parameters and forward rf signal detected by a diode detector at 110 GHz (left) and 138 GHz (right) for oscillations of 1 MW for 10 s.

2.3 Long-pulse (198 s) oscillations

After demonstrating the above results, we improved the TL for longer pulse oscillation or higher energy injection up to 100 MJ. In order to reduce a risk of arcing in the TL and the gyrotron, we started to operate the gyrotron at 0.5 MW with the improved TL. In December 2013, we obtained an oscillation of 0.51 MW for 198 s at 110 GHz, which is the maximum pulse length available with the present control system. After the annual maintenance period of power supplies of ECH/ECCD system from January to March in 2014, the conditioning operation was restarted at 138 GHz, and an oscillation of 0.53 MW for 198 s was obtained in April 2014. Figure 3 shows the operating parameters of the long-pulse oscillation of 198 s at both frequencies. In this case, the V_{ak} at 138 GHz is larger than that at 110 GHz again, while the heater P/S current and acceleration voltage were the same as that for 110 GHz. In these oscillation, we observed no problems on the gyrotron itself, and the temperature rise in the transmission line was around 100 °C or smaller than that. The temperature rise in the cooling water and fluorinert of the gyrotron and MOU were almost saturated, and the peak temperature rise was sufficiently low.

Since the output energy obtained by the long-pulse oscillations (100 MJ) is the comparable with the target of the JT-60SA, these results shows a good prospect toward demonstration of oscillations of 1 MW for 100 s at both frequencies. Long-pulse operation at 1 MW will be carried out in near future.

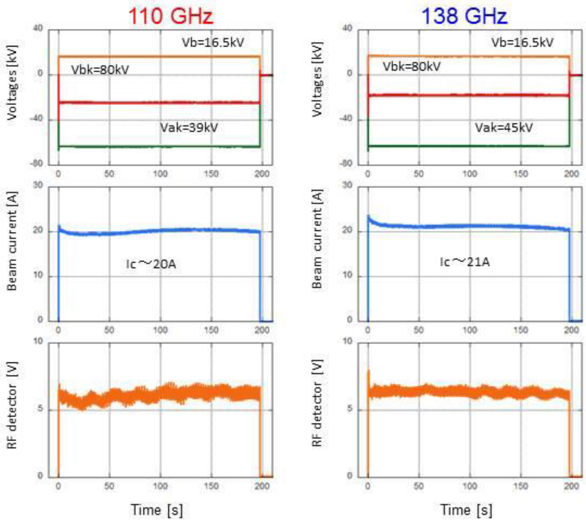

Figure 3. Temporal behaviour of operation parameters and forward rf signal detected by a diode detector at 110 GHz (left) and 138 GHz (right) for oscillations of ~0.5 MW for 198 s.

3 Oscillations at 82 GHz

In JT-60SA, the millimetre waves of both 110 GHz and 138 GHz are injected as second harmonic resonance waves at the toroidal field of 1.7 T – 2.3 T. However, fundamental harmonic waves are sometimes useful for experiments in various conditions. Since the JT-60SA magnet system uses super-conducting coils, toroidal field is excited during a day of operation. Therefore, a Taylor discharge cleaning (TDC), which is reliable wall-cleaning method in tokamak device, is not available between shots. Thus, alternative way of the wall-cleaning is needed. In JT-60SA, ECH wall-cleaning is planned. In the previous JT-60, an effectiveness of the ECH wall-cleaning using fundamental harmonic waves was demonstrated by K. Itami et al [17]. However, the effectiveness of the second harmonic waves for ECH wall-cleaning is not

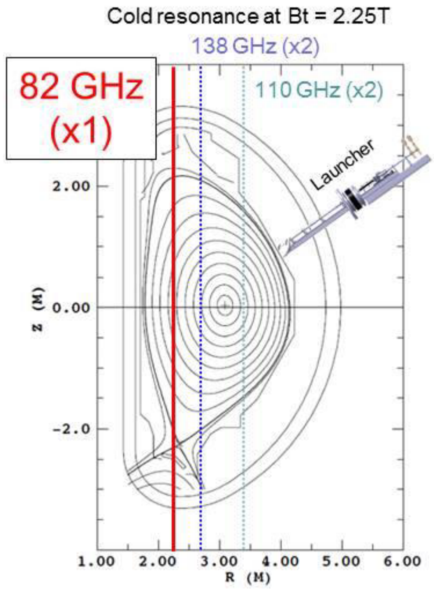

Figure 4. An example of cold resonance surface at the toroidal field of 2.25 T for 82 GHz (fundamental), 110 GHz (second harmonics), and 138 GHz (second harmonics).

clear, so far. Moreover, ECH assisted start-up is well known way to reduce required CS coil flux. Since the CS coil of JT-60SA is also super-conducting coil, the available flux is limited and ECH assist will be required in many experiments. In this purpose, the fundamental harmonic waves are more effective than the second harmonic waves to reduce the required ECH power [18].

In the design of the above mentioned dual-frequency gyrotron in 2011, we considered a possibility of the oscillation at 82 GHz as an additional frequency of the dual-frequency gyrotron. The 82 GHz wave can be used as a fundamental harmonic wave in JT-60SA at the toroidal field of 2.3 T as shown in Fig. 4. Since the purpose of the development of this gyrotron is to enable oscillations of 1 MW for 100 s at two frequencies of 110 GHz and 138 GHz, optimization for triple frequencies has risks for achieving the original purpose. However, if the purpose of the additional frequency is ECH wall-cleaning and ECH assisted start-up, the power and pulse length for these purposes are 0.5 MW – 1 MW and 0.5 s – 1 s. In the design, we found that it is possible to oscillate at 82 GHz with an output power of 1 MW at beam current of > 50 A, acceleration voltage of 80 kV, and the electron pitch factor of 1.1. Moreover, we found that the well centered beam pattern at the output window can be obtained with small modification of the curvature of the internal mirrors without large impact on the beam pattern and diffraction loss at 110 GHz and 138 GHz. Figure 5 (top) shows calculated beam patterns at the output window for each frequency. It is noted that the calculated diffraction loss is comparable with that of the original 110 GHz gyrotron used in JT-60, which successfully generated 1 MW for 5 s [2].

In 2013, an initial experiment of 82 GHz oscillation was carried out, and an oscillation of 0.3 MW for 20 ms was obtained, so far. The output pattern obtained at the inlet of the MOU agreed with the calculated pattern as shown Fig. 5 (bottom). The frequency was also measured by using an even harmonic mixer and agreed with design. Since the pulse length was limited by a short pulse dummy load used in this experiment, we will try to increase output power and pulse length toward 1 MW and 1 s at this additional frequency of 82 GHz in future.

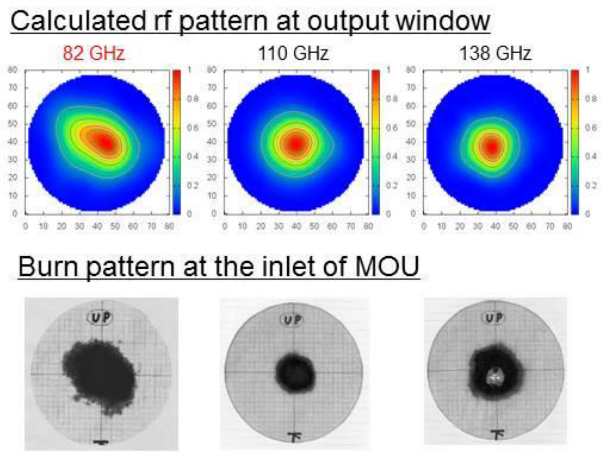

Figure 5. Calculated rf patterns at the output window and burn patterns at inlet of the MOU for 82 GHz, 110 GHz, and 138 GHz.

Summary

In JAEA, a dual-frequency gyrotron (110/138 GHz) is being developed for the use in JT-60SA ECH/ECCD system. So far, oscillations of 1 MW for 10 s and ~0.5 MW for 198 s were obtained at both frequencies. Since the measured diffraction loss is sufficiently low for longer pulse oscillation, oscillations of 1 MW for 100 s at both frequencies are expected in near future by continuing conditioning operation. In order to confirm a possibility of the fundamental harmonic wave at 82 GHz in JT-60SA, an oscillation of 0.3 MW for 20 ms at this frequency was demonstrated as an additional frequency of the dual-frequency gyrotron. These development results contribute to significant extension of the operation region of the ECH/ECCED system in JT-60SA.

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