Progress and status of the gyrotron development for the JT-60SA ECH/CD system

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***Abstract*—High-power, long-pulse operations of a gyrotron for JT-60SA (Super-Advanced) have been carried out at 110 GHz (1 MW/100 s) and 138 GHz (1 MW/100 s). These results fully satisfied the requirements of the electron cyclotron heating and current drive (ECH/CD) system in JT-60SA. It was experimentally shown that the higher power operation at each frequency is expected to be acceptable for this gyrotron from the viewpoint of heat load at the cavity resonator, collector, and stray radiation absorbers. An oscillation of 1 MW for 1 s at 82 GHz has been demonstrated as an additional frequency of the same gyrotron. Experiments toward 1.5 MW or higher at 110 GHz and 138GHz are ongoing.**

I. INTRODUCTION

THE electron cyclotron heating and current drive (ECH/CD) system is one of the key systems in JT-60SA [1]. Since JT-60SA is a super conducting tokamak, start-up assist [2] and wall cleaning [3] by ECH/CD are essential tools. In 2011, a detailed design and fabrication of a new gyrotron for JT-60SA was started [4]. The main target of this development is to demonstrate oscillations of 1 MW for 100s at two frequencies of 110 GHz and 138 GHz by the same gyrotron tube. The frequency of 110 GHz is effective for ECH/CD at the toroidal magnetic field, B_t, ~1.7 T (typically for high-beta steady-state scenarios in JT-60SA) and the frequency of 138 GHz is effective for ECH/CD at B_t ~ 2.3 T (typically for the scenarios with the highest plasma current of 5.5 MA in JT-60SA) [5].

High-power, long-pulse operations have been carried out to demonstrate oscillations of 1 MW for 100 s at both frequencies. In addition, an oscillation at an additional frequency of 82 GHz has been demonstrated by the same tube. This frequency is effective for plasma start-up assist and wall cleaning since the fundamental harmonic resonance wave is available in JT-60SA instead of the second harmonic resonance waves by the above two frequencies.

This paper describes a progress of the gyrotron development in 2014-2015 for high-power operations at 110, 138 and 82 GHz in JT-60SA.

II. STATUS OF THE JT-60SA ECH/CD SYSTEM

Manufacturing and installation of main components of the JT-60SA tokamak, such as the vacuum vessel, the super conducting coils, and the cryostat, are ongoing. The first plasma discharge of JT-60SA is planned in March 2019. Since JT-60SA is a super conducting tokamak, an available one turn voltage for start-up applied by the central solenoid coil is limited compared to that in the previous JT-60U tokamak. It is known that an assist by ECH through pre-ionization of the neutral gas results in a reduction of the required one-turn voltage for plasma start-up [2]. Moreover, Taylor-type discharge cleaning (TDC), which is one of the effective wall

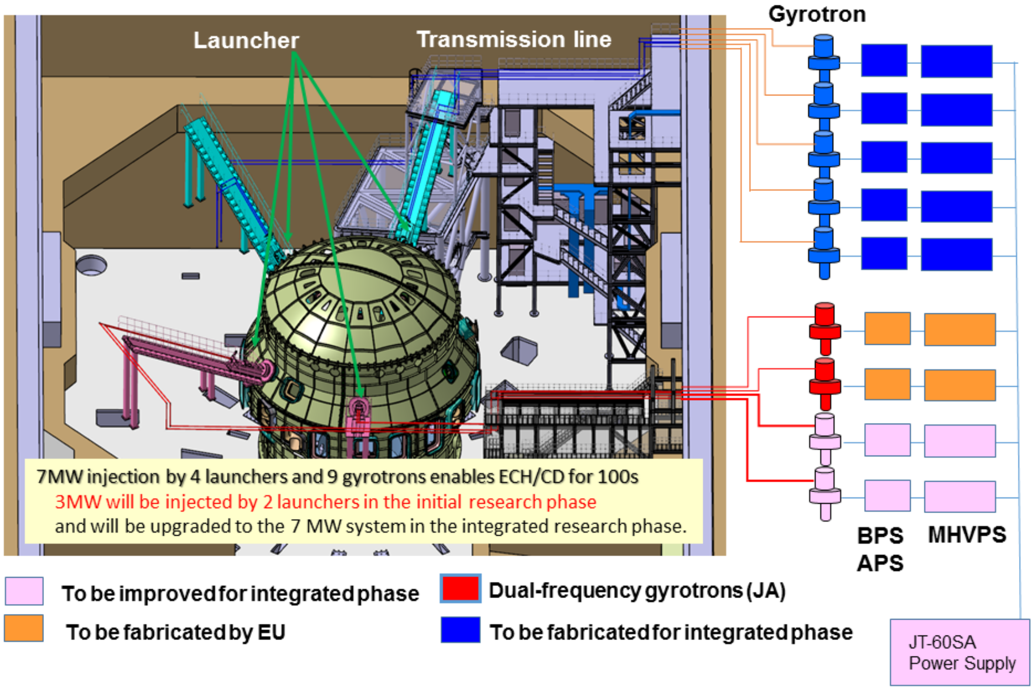

Fig. 1 Outline of the ECH/CD system of JT-60SA.

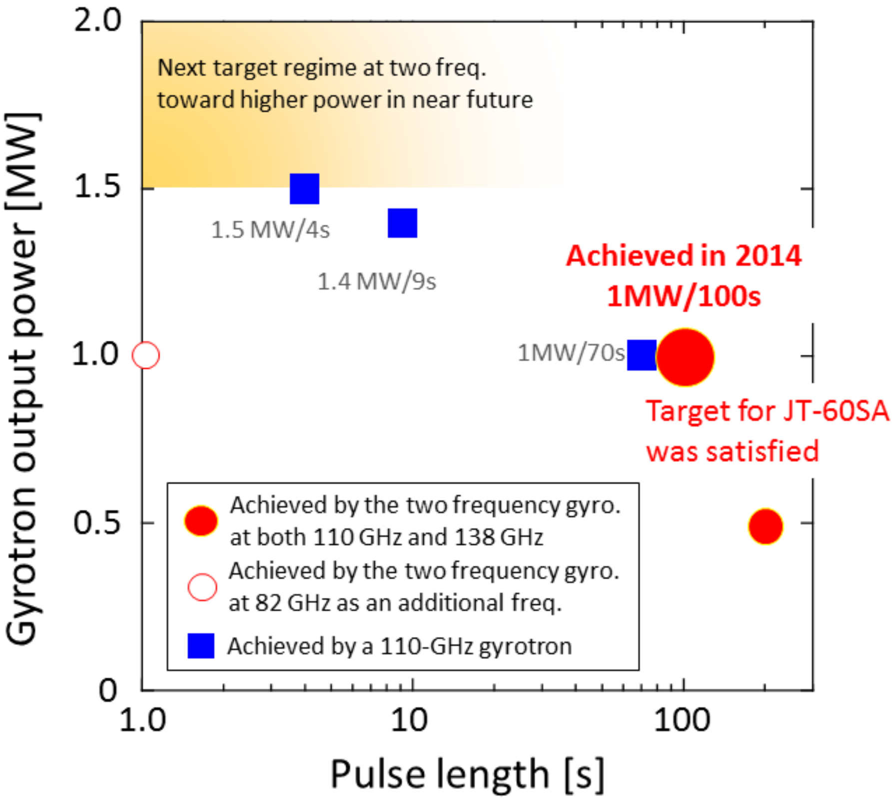

Fig. 2 Gyrotron output power and pulse length achieved, so far, by a two frequency gyrotron for JT-60SA at both 110 GHz and 138 GHz (closed circles) and at 82 GHz as an additional frequency (open circle), and the achievement by a 110 GHz gyrotron for JT-60 (closed rectangles). The next target regime at two frequencies to be developed in near future toward higher power is a region with an output power of ~1.5 MW or higher.

cleaning methods between shots applied in many tokamaks, is not available in super conducting tokamaks. Instead of TDC, ECH discharge wall cleaning [3] will be applied in JT-60SA. From the above reason, the ECH system is an essential tool for JT-60SA even in the commissioning phase and the early operation phase.

Figure 1 shows the outline of the ECH/CD system of JT-60SA. Modification/improvement of the existing ECH/CD systems used in JT-60U are ongoing in parallel to the R&D of the two frequency gyrotron, launcher and transmission line. Toward successful start of the experiment in 2019, manufacturing and installation of the improved or newly developed ECH/CD system components will be carried out mainly in 2016 – 2018.

III. HIGH-POWER, LONG-PULSE OPERATION AT 110 GHZ AND 138 GHZ

The key issues to get high-power are to reduce cavity Ohmic loss (typically < 2 kW/cm^2) and to obtain high oscillation efficiency (typically > 30% without collector potential depression (CPD)) for reducing collector heat load. In the high-power experiment, we confirmed that the cavity heat load at 110 GHz was smaller than that of the previous gyrotron, because we increased the operating mode number from $TE_{22,6}$ to $TE_{22,8}$. It is noted that the output power of 1.5 MW for 4 s and 1.4 MW for 9 s was obtained by the previous 110-GHz gyrotron as shown in Fig.1 (closed rectangles). Thus it is expected that the cavity loss of the new gyrotron is sufficiently low for output power of >1.5 MW at 110 GHz. Moreover, the high oscillation efficiency (without CPD) of 34% at 110 GHz and 32% at 138 GHz was obtained at the output power of 1 MW. The result was obtained by optimizing anode voltage of the triode type magnetron injection gun to optimize the electron pitch factor at each frequency.

The key issue to achieve long pulse is to reduce stray radiation due to diffraction loss in the gyrotron. The internal mode convertor was designed by using LOT/Surf3D code [7]. The chosen operating modes of $TE_{22,8}$ (110 GHz) and $TE_{27,10}$ (138 GHz) have similar transverse radiation angles in the mode convertor resulted in relatively low loss (<5%) at both frequencies. In high-power experiment, we confirmed that the increase in the ion pump current, which is a measure of the increase in the pressure due to temperature rise of internal components heated by stray power, was sufficiently low for 100 s operation and further long-pulse is acceptable.

As a result of the high-power, long-pulse experiments with the above experimental evaluation of heat loads, we have demonstrated oscillations of 1 MW for 100 s at both frequencies and the target for JT-60SA has been fully achieved as shown in Fig. 2 (closed circles). More details of the gyrotron oscillation characteristics and evaluation of internal and external losses are discussed in ref. [8]. Since heat load at each component is acceptable to increase power, experiments toward higher output power of 1.5 ~ 2 MW is ongoing.

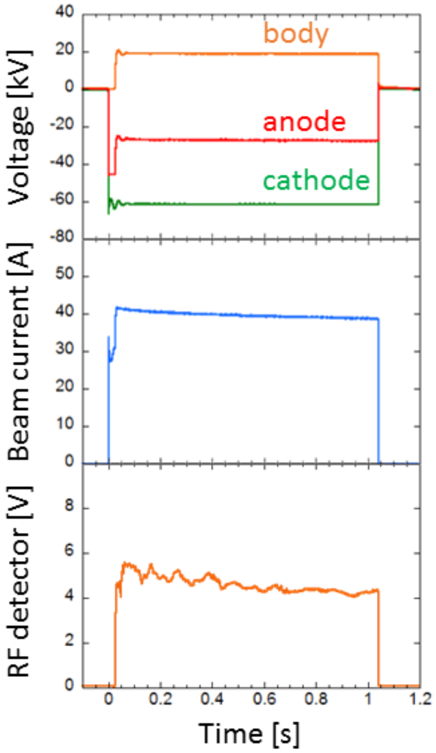

Fig. 3 Time evolutions of voltages applied to the gyrotron electrodes, beam current, and the RF detector signal (diode) during an oscillation of 1 MW for 1 s at 82 GHz.

IV. EXPERIMENTAL RESULT AT 82 GHZ

The thickness of the gyrotron output window was design to have small reflection at the frequency of 82 GHz as well as 110/138 GHz. Because we carefully selected operating mode ($TE_{17,6}$ for 82 GHz) and slightly adjusted internal mirror shape also for this frequency, it is acceptable to operate at 82 GHz with an output power of ~1 MW for short pulses of ~1 s, in design. In 2014, an oscillation of 0.4 MW for 2 s was obtained at 82 GHz by conditioning operation of few weeks. After annual maintenance of ECH power supplies, we restarted the conditioning operation at 82 GHz in June 2015. An oscillation of 1 MW for 1 s (open circle in Fig. 2) has been obtained successfully by conditioning operations of about 2 weeks. A conditioning was needed for reducing outgas in the transmission line and not for gyrotron. Figure 3 shows the time evolutions of voltages applied to the gyrotron electrodes (cathode, anode and body), the beam current and the RF detector signal. Since the diode detector, which was installed at the directional coupler of the miter bend in the transmission line with an additional directional coupler, has frequency dependence, the diode detector signal varied during the one second due to slightly varying operating frequency by a thermal expansion of the cavity resonator. The acceleration voltage and beam current were 80 kV and 40 A, respectively, in this operation. It is noted that the optimum voltage between anode and cathode at 82 GHz was lower than that for 110/138 GHz at the fixed acceleration voltage.

We measured the operating frequency by a heterodyne circuit using an even harmonic mixer (× 8), a local oscillator of 10.05 GHz (measured range of 80.4 GHz +/- 2.9 GHz) or 10.55 GHz (measured range of 84.4 GHz +/- 2.9 GHz) and a spectrum analyzer with some low/high/band pass filters. The measured frequency at the 1 MW oscillation was around 82.5 GHz as expected.

We also evaluated the diffraction loss in the gyrotron. The measured total loss power was ~ 7.5% of the output power at 82 GHz. This value was approximately twice higher than that at 110/138 GHz since the mode convertor was optimized for only 110/138 GHz and not optimized for 82 GHz. However, the loss is lower than that of the original 110 GHz gyrotron (~9.5%) used in JT-60 [9]. It should be mentioned that the original 110 GHz gyrotron has a capability of 1 MW for 5 s and 1.5 MW for 4 s. Thus, it is expected that the JT-60SA gyrotron has a sufficient margin for cyclic operations at 82 GHz from the viewpoint of the total diffraction loss by limiting the output power and the pulse length up to 1 MW and 1 s, which will be sufficient for the purposes of start-up assist and wall cleaning.

We have never observed severe problems at this frequency, so far, during repeated oscillations of 1 MW for 1 s for the purpose of the above measurements.

V. SUMMARY

Remarkable results were obtained in the gyrotron developments for JT-60SA. The two frequency gyrotron successfully operated at 1 MW for 100 s at two frequencies as expected in design. The higher power operation is expected to be acceptable from the viewpoint of the experimental evaluation of the head load of each component. Moreover, an oscillation of 1 MW for 1 s at the additional frequency of 82 GHz was demonstrated by the same gyrotron. These results significantly contribute to extend operation regime of the ECH/CD system in JT-60SA.

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