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A High-Power Gyrotron and high-power mm wave technology for Fusion Reactor

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Recent activities on the developments of high power gyrotrons and high power millimeter wave technologies in JAEA are presented. A basic criterion of ITER gyrotron was satisfied using a JAEA $TE_{31,8}$ mode gyrotron. The output power from the gyrotron is used for developments of transmission line components and ITER launcher. The gyrotron is being operated for 3 years, and demonstrated operational reliability. As a next step, a new gyrotron was designed and fabricated, which operates at higher order resonator mode to enable the operation at greater than 1 MW. In parallel, feasibility studies of power modulation and dual frequency gyrotron were carried out. On 110GHz gyrotron system of JT-60U, 2.9MW power injection into the plasma was demonstrated for 5 sec pulse duration. The EC technologies under development for ITER and JT-60SA are applicable also for future fusion reactors such as DEMO.

Keywords: Gyrotron, mm-wave technology, $TE_{31,8}$ mode, ITER, DEMO

1. Introduction

On ITER (International Thermonuclear Experimental Reactor), a 20 MW electron cyclotron heating and current drive (EC H&CD) system is being planned for a plasma initiation, heating, current drive and MHD instability control [1,2]. As a power source, 1MW 170GHz long pulse gyrotron is required. A development of the 170 GHz gyrotron has been carried out from EDA phase (Engineering Design Activities) in Russia, Europe and Japan [3,4]. In 1990's, important breakthrough technologies for high power long pulse gyrotrons, such as a high efficiency mode converter [5], depressed collector [6], diamond window [7-9], were developed, which gave a route to the realization of 170 GHz 1MW CW gyrotron. In 2000's, quasi-CW operations were demonstrated by some gyrotrons. On 140 GHz gyrotron developed for Wenderstein 7X, by using an advanced built-in mode converter, 30 min operations were demonstrated by EU and US in 2003-2005 [10,11]. In 2006, a stable 1MW 170 GHz oscillation was demonstrated at CW-relevant pulse duration. Here, the efficiency was 55 % with a depressed collector at the optimum oscillation parameters in the so-called hard excitation region [12]. The achieved parameters satisfy a basic criterion required for the ITER gyrotron. Using this gyrotron as a power source, R&D of a transmission line and a launcher for ITER procurement is underway in addition to the reliability test of the gyrotron. As a next activity, the gyrotron development of higher power generation using a higher resonator mode has started. A resonator diameter is raised by increase the mode number in the resonator, which reduces a heat load density on the resonator wall. And, feasibilities of a power modulation for application to the Neo-classical Tearing Mode (NTM) suppression of ITER plasma and frequency tunability are studied for advanced operation. In parallel, the EC H&CD technologies developed for ITER have been applied for 110 GHz system on JT-60U.

In this paper, recent activities and next plan for EC H&CD technologies at JAEA are described. In section 2, present deign of ITER EC H&CD system is introduced. In section 3, experimental results of 170 GHz gyrotron are described, and tests of transmission line and launcher are described in section 4. R&D for an advanced gyrotron is discussed in section 5. In section 6, results of 110 GHz EC H&CD system on J-60U are summarized. A conclusion is given in section 7.

2. EC H&CD system of ITER

For the 20 MW EC H&CD system of ITER, 24 tubes of 1 MW-170 GHz gyrotron will be adopted assuming a transmission efficiency of 83 %. In the transmission line, various components such as a matching optics unit (MOU) that interfaces the gyrotron output power with the waveguide, 8~9 miter bends, 1~2 isolation valves, a torus window for tritium shielding, and a launcher, are included. The development of the launcher and demonstration of high efficiency high power transmission are important R&D issues for ITER EC H&CD system (section 4). The 24 gyrotrons are placed in the third floor of the RF building to be built adjacent to

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the assembly hall of ITER as shown in Fig.1 [13]. Main power supplies are placed in the first floor, and beam acceleration power supplies [14] are placed in the second

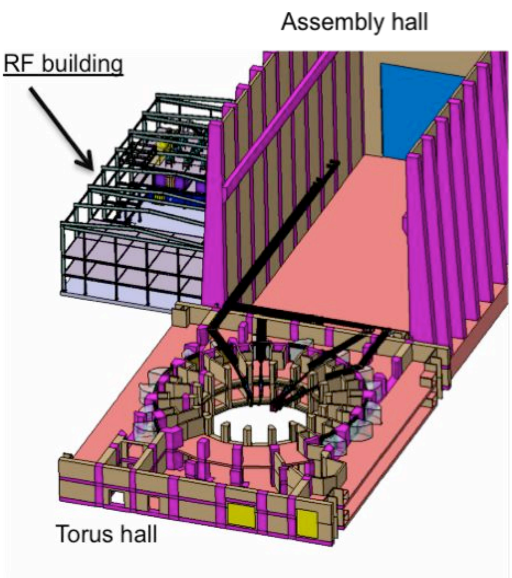


Fig.1 Layout of RF heating system and torus hall of ITER. (Courtesy of M.Henderson of ITER/IO)

floor of the RF building. The length of the transmission line will be ~150 m. Two types of the launcher are installed. One is the launcher installed in an equatorial port to perform the heating and current drive. Other is four launchers in upper ports, which have the control function of MHD instability [2].

3. 170GHz 1MW Gyrotron for ITER

The JAEA gyrotron has following feature [15]. An electron gun is a triode-type magnetron injection gun (MIG). In the beam tunnel, which indicates a section between the MIG and a resonator, conical silicon carbides are installed to suppress a parasitic oscillation. The resonator is a cylindrical cavity, whose Q-factor is 1530 at 170 GHz-$TE_{31,8}$ mode. A built-in mode converter placed at the downstream of the resonator is designed to generate a Gaussian beam using CCR-LOT and Surf3D codes [16]. The RF beam radiated from the converter is transformed with 4 mirrors and is outputted through the diamond window of 1.853 mm in thickness. The disk edge is coated by Copper to protect the bonding material between the cuffs and the diamond from the corrosion. In the operation, a pitch factor of the electron beam can be controlled by the changing the anode voltage V_{ak}. With a combination of resonator field B_c (magnetic field at the resonator), electron parameters (cyclotron frequency and pitch factor) can be optimized actively during the oscillation.

In Fig.2, a history of the gyrotron operation is shown. Operation begun at March 2006, and some important results, such as 1 hour oscillation, 1 MW/800 s/55 %, 0.8

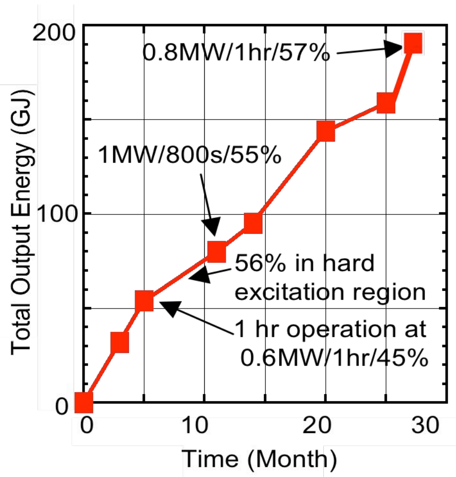


Fig.2: History of integrated RF energy outputted from the JAEA170 GHz gyrotron. Start was March of 2006.

MW/1 hour/57 %, have been demonstrated as indicated in the figure. The total output energy is ~200 GJ. The output power and deposition power in the tube was measured calorimetrically [17]. Sum of measured powers, i.e., output power from the window (1020 kW), collector deposition (742 kW), a stray radiation (24kW) and ohmic loss (63 kW), agrees well with the DC input power. In Fig.3, the beam current dependence of the output power and the efficiency with and without the depressed collector are shown. Pulse durations for all data are greater than 5 min. By the active control of V_{ak} and B_c, the operation parameters (electron cyclotron frequency and its pitch factor in the resonator) are optimized for each data in the hard excitation region. The maximum efficiency was ~60 % at 0.6 MW output. Fig.4 shows a time evolution of one-hour operation for the applied voltages, beam current (~30A), magnetic field at the resonator, light signal observed in the tube, RF signal at the directional coupler, vacuum in the tube at the output power of 0.8 MW. The efficiency was 57%. The oscillation was very stable during the shot. The pressure increased for 40 min, however, that kept a constant value after 40min. This pressure stabilization can be explained as follows. During the operation, the electron beam ionizes neutral particles in the tube. These positive ions are accelerated by the strong electric field applied for the depressed collector and those are absorbed by the collector wall. In other words, the depressed collector gyrotron acts as an ion pump inherently. When the operation ended, such pumping effect disappears. Consequently, increase in the pressure occurs because the ions are released from the collector wall and no additional pumping effect.

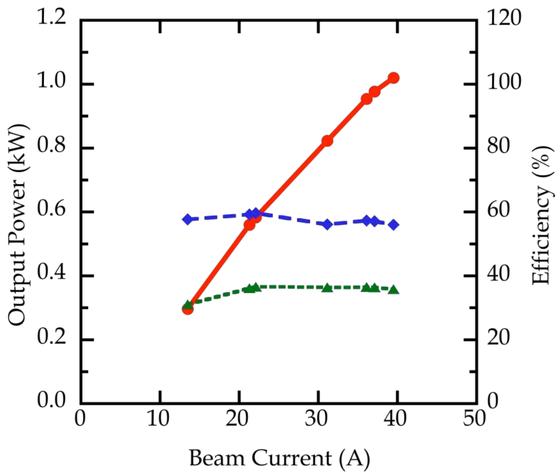


Fig.3: Experimental result of beam current dependence of output power at 170 GHz (red), oscillation efficiency (green) and overall efficiency with depressed collector (blue). Beam voltage is ~72 kV, anode voltage, depressed collector voltage, B_c are optimized for each data points. Pulse durations are greater than 5min.

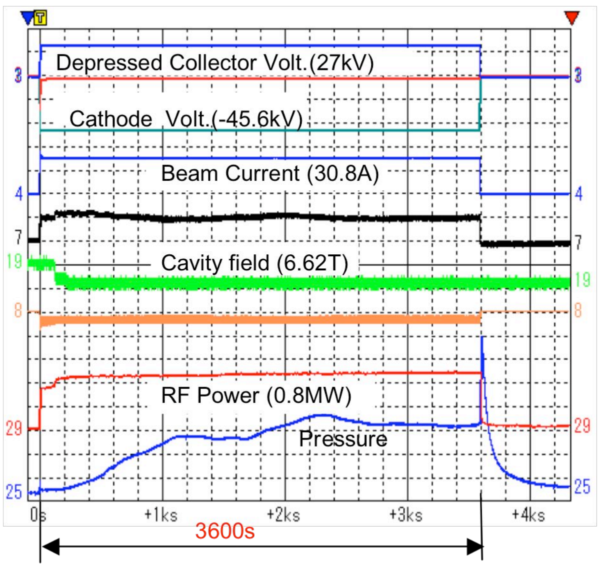


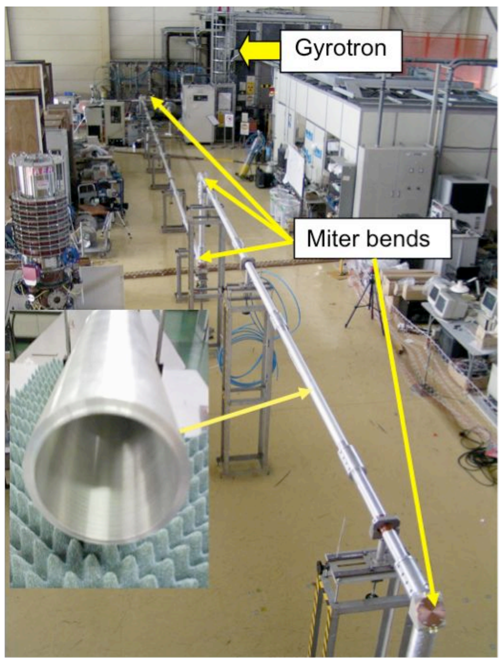
Fig.4: Time evolution of 1-hour operation of 170 GHz gyrotron at 0.8 MW. The efficiency is 57 % with the depressed collector.

As a simulation of gyrotron operation on ITER, a high repetitive RF generation was demonstrated at 0.8 MW. Ten shots were repeated for every 30 min with the pulse duration of 400sec. The efficiency with the depressed collector was ~56%. No major trouble was observed, which gives a prospect of stable operation in ITER experiment [18].

4. RF power transmission and launcher for ITER

The output power of the gyrotron is used for developments of transmission line and launcher components [19]. In Fig.5, picture of the test transmission line in JAEA is shown. The output power couples with the waveguide of 63.5mm in diameter via two-phase correlation mirrors in a matching optics unit (MOU), and 92 % of the output power was transmitted to the dummy load via 40 m evacuated transmission line including 7 miter bends. Here a power loss in the MOU is ~4.5 %. At the end of the transmission line, components, such as a torus window for ITER, arc detector, low loss miter bend, polarizer, are connected for high power and long pulse tests. Furthermore, as with the practical system, a test launcher is connected after the transmission line.

For this purpose, a preliminary launcher mock-up was manufactured as shown in Fig.6. Fig.6(a) shows one of three quasi-optical RF beam lines of the equatorial launcher [20]. Fig.6 (b) is a picture of the launcher mock-up fabricated based on the updated design of the equatorial launcher. High power mm wave is outputted from one waveguide, and radiated from the movable mirror. The radiated power is reflected by two mirrors and outputted from the launcher as a bundle of the beams. The surfaces of two mirrors are optimized to minimize the heat load on the mirrors [21]. The angle of the final



40m Waveguide +7 bends

Fig.5: Picture of transmission line of JAEA test stand.

mirror can be controlled using an ultra-sonic motor. The power is received by a metal dummy load.

The test system includes most of the essential parts of ITER EC H&CD system. The test on this system will provide useful database for the detailed design of the system.

5. Advanced Gyrotron

5.1 Higher mode oscillation of 170 GHz gyrotron

The R&D of a high power gyrotron using a higher mode oscillation has started. The oscillation mode is $TE_{31,12}$ cylindrical resonator. By increasing the oscillation mode, the resonator diameter increases from 17.9 mm to 21.84 mm, and the heat load on the resonator wall significantly decreases. This will contribute to the higher power generation and relax a thermal stress on the resonator. On the other hand, careful setup and operation will be required to establish the stable and high efficiency oscillation. The MIG is the same configuration with the $TE_{31,8}$ gyrotron. As a first step, a short pulse gyrotron was fabricated and tested. The output power of ~1.57 MW was obtained at 170 GHz. Based on the result, a long pulse $TE_{31,12}$ mode gyrotron was fabricated as shown in Fig.7. The experiment will be done soon.

5.2 Power modulation

In ITER, high frequency power modulation up to 5 kHz will be required for suppression of NTM instability. For this purpose, a test of high power modulation of JAEA gyrotron is planned using a voltage modulation of a body power supply [14]. Generally, when the power modulation is applied, the collector heat load increases since the non-workout electron beams impact the collector. In case of the JAEA gyrotron, however, the modulated voltage of the body V_m appears as a decrease in the anode-cathode voltage V_{ak} of the triode MIG since the anode-body voltage is kept constant. Since a beam current decreases as the V_{ak} does, the current drop by the voltage modulation must be much larger than the diode type MIG. Furthermore, if the anode modulation is added on, V_{ak} will decrease to 0V. Consequently, the beam current could be reduced to small level. Then, the averaged collector heat load can be suppressed significantly, which will permit the operation at larger beam current to increase the oscillation power on the identical gyrotron.

Fig.7: Picture of 170 GHz gyrotron. Oscillation mode is $TE_{31,12}$, and Gaussian beam output.

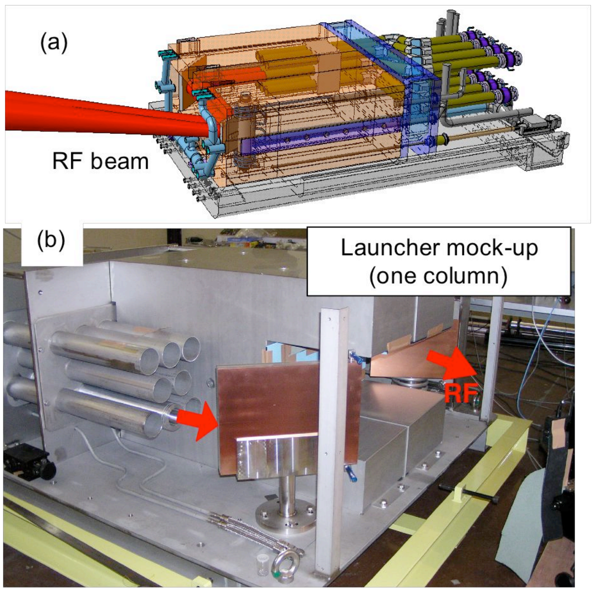


Fig.6: Mockup of equatorial launcher. (one of three beam lines).

5.3 Dual Frequency gyrotron

High power multi-frequency gyrotrons have been studied by many institutes [22-24]. These gyrotrons have a diode MIG. Generally, the triode has a larger flexibility than the diode for determination of electron beam parameters such as beam radius, pitch factor at fixed beam voltage. Therefore, the triode type MIG is much suitable for the multi-frequency gyrotron. Here, a set of $TE_{31,11}$ and $TE_{25,9}$ modes for 170 GHz and ~137 GHz, respectively, are proposed. The mode corresponds to the transparent frequency of the diamond window of 1.853 mm in thickness. By adjusting the anode voltage the mirror ratio between the resonator and MIG fields, optimized pitch factor can be selected at any beam voltage. Consequently, 1 MW high efficiency oscillation will be available at both modes. The high efficiency mode conversion is also available from the oscillation mode to the Gaussian beam for both modes.

5.4 Fast field control super conducting magnet

For a step tunable frequency control at reasonable beam parameters, a magnetic field control should be accompanied. For a fast control of B_c, He-free super conducting magnet with an additional sweeping coil was developed [25]. A diameter of a room temperature bore is 240 mm, and the 7 T at the center. Using commercially available DC power supplies, the magnetic field sweeping was demonstrated with a speed of 0.4 T/10 sec at 7T.

6. 110 GHz gyrotron for JT-60U and JT-60SA

The 110 GHz gyrotron has been designed firstly in 1998 taking into account the results of 170 GHz gyrotron in ITER. The basic configuration is the same with the 170 GHz gyrotron. The oscillation mode is $TE_{22,6}$ at 110 GHz. The MIG is the triode gun, and the depressed collector is adopted. The thickness of the diamond window is 1.715mm. The EC H&CD system was firstly applied on JT-60U in 1999, and upgraded to 4-gyrotron system in 2001. Liquid He free magnets have been used for all gyrotrons, and no major trouble had occurred. The EC H&CD was used on JT-60U, and many important results were demonstrated on the large sized plasma, such as electron heating to 26 keV [26], plasma initiation by second harmonic ECR [27] and NTM suppression [28]. In 2008, the total injection power of 2.9 MW for 5 sec was demonstrated [29] and its operation has ended on JT-60U. In the last experiment campaign, modulated ECCD at 5-7 kHz synchronized to NTM was achieved by real time control of anode voltage [30] and stronger stabilization effect was obtained than un-modulated ECCD by a factor of more than 2 [31]. The improvement of EC H&CD system has started aiming 100sec operation on the future JT-60SA. In parallel, the effort for improvement of 110 GHz gyrotron performance is continued after the JT-60U shutdown. Up to now, the demonstration of 1.5 MW/1 sec has succeeded [32]. Here, the beam voltage and the beam current are 86 kV, 62.8 A with the depressed collector voltage of ~26 kV. In the near future, the experiment will be continued using the gyrotron where the improved mode converter is installed.

7. Conclusion

A basic requirement of the ITER gyrotron performance was demonstrated with the JAEA 170 GHz gyrotron. As the next activity, higher order mode gyrotron is under development for a higher power generation. In parallel, the demonstration of the power modulation is planned for ITER application. And, a design of a dual frequency gyrotron was proposed. The high power gyrotron is used as a power source for the developments of transmission line and ITER launcher. The full performance of EC H&CD system was demonstrated on JT-60U with 110 GHz gyrotrons, where 2.9 MW/5 sec injection was attained. These activities give a prospect for the procurement for ITER and JT-60SA. As the EC technologies have a generality, R&D carried out for ITER and JT-60SA are also applicable for all kind of magnetic fusion devices and future reactor DEMO since the present design of the magnetic filed strength is similar level [33].

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