Development of Gyrotron and JT-60U EC Heating System for Fusion Reactor

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Abstract. The progress of ECH technology, for ITER and JT-60U tokamak, are presented. In the development of gyrotron, 0.9MW/9.2sec, 0.5MW/30sec, 0.3MW/60sec, etc. have been demonstrated at 170GHz. At 110GHz, 1.3MW/1.2sec, 1.2MW/4.1sec, 1MW/5sec were obtained. It is found that the reduction of the stray radiation and the enhancement of cooling capability are keys for CW operation. Four 110GHz gyrotrons are under operation in the ECH system of JT-60U. The power up to approximately 3MW/2.7sec was injected into the plasma through the poloidally movable mirrors, and contributed to the electron heating up to 26keV(n_e~0.5×10^{13}cm^{-3}), and the suppression of the neo-classical tearing mode.

1. Introduction

The Electron Cyclotron (EC) wave is an effective method of on- and off-axis current drive and plasma profile control for fusion reactors. Injection of 20 MW EC power is planned in the ITER design to suppress the Neo-Classical Tearing Modes (NTMs). A 170GHz, 1 MW gyrotron is a key R&D technology of the ITER EC system and intensive efforts have been made in JAERI to develop the 170GHz gyrotron. During ITER EDA, successes of introducing the depressed collector[1], high order mode oscillation at 170GHz/1MW[2] and installation of a CVD diamond window on the gyrotron[3-5] opened a new stage of gyrotron development. Further advancement to suppress unnecessary modes like parasitic oscillations was achieved[6]. Together with these, integration efforts of the key EC technologies have also been devoted in the 110GHz EC system on JT-60U. The construction had been started in 1998 by use of the technology outcomes of ITER R&D and the system with four 1MW gyrotrons started its operation in 2001[7]. In the following sections, the latest results of development of gyrotrons and ECH system on JT-60U are described.

Fig.1: Appearance of 170GHz gyrotron. Height is ~3m.

2. Gyrotron Development

2.1 170GHz gyrotron

A photograph of the 170GHz gyrotron and a cross sectional view of the gyrotron are shown in Fig.1 and Fig.2, respectively. A triode type electron gun (magnetron injection gun: MIG) and mirror magnetic field makes a rotating electrons with an energy of 70keV~ 85keV, which are injected into a cylindrical cavity and generate $TE_{31,8}$ mode RF of more than 1MW. Q-factor of the cavity is 1530. The oscillation power is converted to the Gaussian beam using a quasi-optical mode converter and outputted through the low loss diamond window. The design value of the radiation power from the window is 94%. A gyrotron experiment was carried out on a gyrotron test stand (RFTS). The capability of RFTS is 90kV/50A for long pulse operation, and

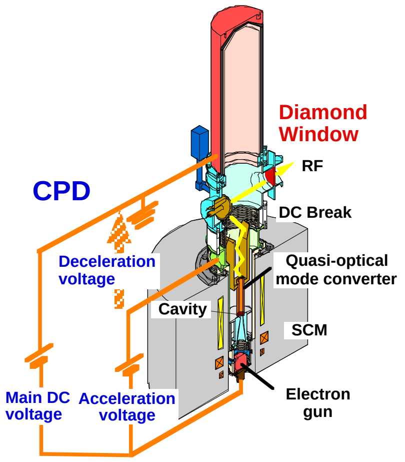


Fig.2: Cross sectional view of depressed collector gyrotron.

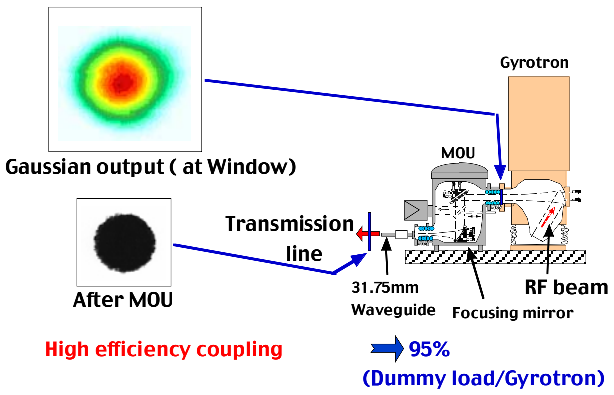


Fig.3: Gyrotron and matching optics unit (MOU) for coupling with waveguide. Measured wave patterns at the gyrotron window and at the waveguide mouth are shown.

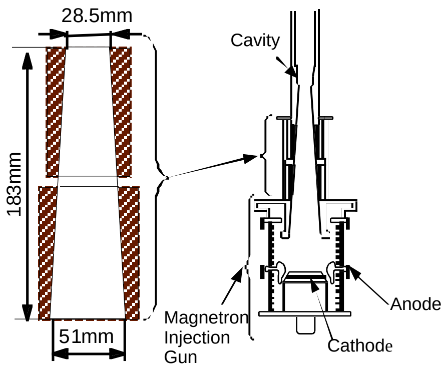


Fig.4: SiC cylinder at beam tunnel for suppression of parasitic oscillation.

90kV/80A up to a few milliseconds. A power supply is consisted of main power supply (MPS) and beam acceleration power supply (APS). The voltage difference between MPS and APS appears as a retarding potential on the spent electron beam at a ceramic insulator (DC break) for a depressed collector operation. A switching of the MPS is done by IGBT (Insulated Gate Bipolar Transistor). The output power is focused to the corrugated waveguide of 31.75mm in diameter using two phase-correction mirrors in the matching optics unit (MOU). As the rf power is radiated as a Gaussian beam through the diamond window, high efficiency coupling is expected. The MOU and transmission line should be evacuated to avoid the breakdown. In the experiment, the Gaussian beam was formed at the window as shown in Fig.3. The transmitted power to the dummy load placed after 12m corrugated waveguide via three miter bends was 95% of the gyrotron power. In the previous 170GHz gyrotron, oscillation efficiency was ~24% at most because a parasitic oscillation occurred in the beam tunnel (a region between the electron gun and the cavity). The frequency of the parasitic oscillation was ~140GHz, which indicates the beam instability due to the cyclotron resonance. The power of the parasitic oscillation was sometimes in the order of a few tens kW, which causes an electron energy broadening and consequently decrease of the main oscillation efficiency. To suppress the parasitic oscillation, SiC cylinders were installed on the surface of the beam tunnel as shown in Fig.4. Since the SiC is a good mm wave absorber, the growth of the instability is anticipated to be suppressed. The adopted SiC cylinders have a finite resistivity, no electrification would occur. As a result, the parasitic oscillation power was suppressed and the output of 1.3 MW with

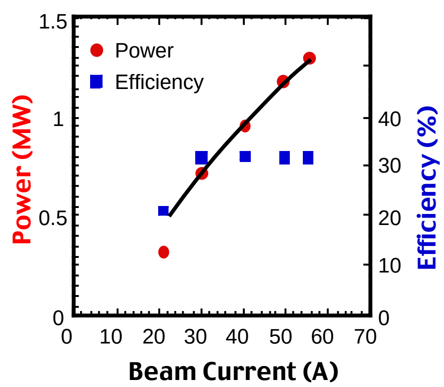
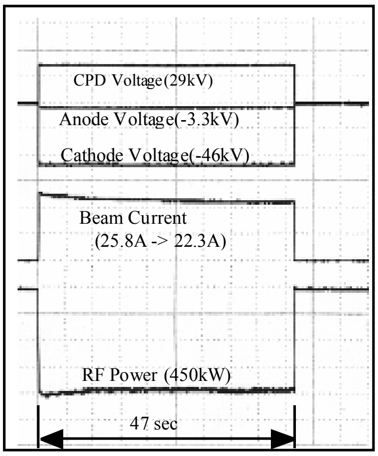


Fig.5: Beam current dependence of Power and efficiency at 170GHz. Beam voltage is ~74.5kV.

31% of oscillation efficiency was achieved. In Fig.5, a beam current dependence of the output power and of efficiency (without depressed collector) is shown. The beam voltage is 74.5kV. The quasi-CW operations have been demonstrated as listed in table 1. Figure 6 is typical waveforms of 47sec operation at 0.45MW output. It is noteworthy that the temperatures of major components like cavity, window and collector stabilized within 5s and operation was quite stable. It took almost no conditioning time to extend the pulse duration from 10 s to 30 s at 500 kW, which gives a promising view to the ITER CW gyrotron. A key point of this fast conditioning is an active extraction of stray radiation power inside the gyrotron through the DC break ceramic and a sub-window. The aperture of the sub-window is 120mm. A material of the DC break ceramic and sub-window is silicon nitride (SN287, Kyocera Co., tanδ~$2x10^{-4}$). The stray radiation was absorbed by water in the Teflon tube and the FX-3300 (3M), which flew around the DC break. The total power of the stray radiation that was extract through the DC break and the sub-window is ~8% of the output power. A power deposition of the stray radiation to the SiC cylinder at the beam tunnel was 0.35% of the output power (mainly to upper one). The pulse extension was prevented by pressure increase in the gyrotron. In Fig.7, the typical behavior of the pressure is shown. Basically, pressure is kept in very low level, but sudden increase of the pressure occurs. The cause was confirmed that the temperature increase of the component of poor cooling (bellows behind the steering mirror that is made of SUS), which absorbed the stray radiation, and probably exceeded a baking temperature 450°C. Further extension of the pulse duration will be achieved by enhancing the cooling capability of the minor sub-components.



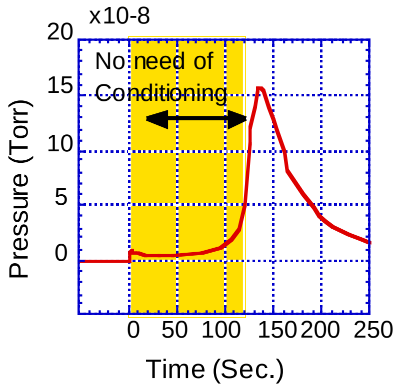


Fig.7: Behavior of pressure in the gyrotron during 0.2MW operation.

2.2 110GHz gyrotron

The 110GHz gyrotron has a same appearance with 170GHz. The oscillation mode is $TE_{22,6}$. Q-value of the cavity is 1300. The heat load on the cavity wall is $1.2kW/cm^2$ at 1MW operation, that is well below the criteria of the heat load of $2kW/cm^2$. The MIG is triode, oscillation power of $TE_{22,6}$ mode is converted to Gaussain beam using the quasi-optical mode converter. The thickness of the diamond disk is 1.715mm. At the beam tunnel, SiC cylinder that has a same size with 170GHz gyrotron is installed. The gyrotron experiment was carried out RFTS using the same magnet. Fig.8 is a beam current dependence of the output power and efficiency at 1msec operation. The beam voltage is 84.5kV. At I_b=57A, the output power was 1.56MW. The maximum efficiency was 33% (1.3MW) at I_b=47A. As with the 170GHz experiment, 94% of the output power was transmitted to the dummy load after three miter bends using a same transmission line. Long pulse operation is underway. Up to now, 1.3MW/1.2sec (efficiency of 48% with depressed collector), 1.2MW/4.1sec 1.0MW/5sec were obtained (Table 1). Since the heat load on the cavity wall has enough margins at 1MW, long pulse operation with higher power such as 1.5MW could be possible.

3. JT-60U EC System

The EC system in JT-60U has similar configuration to the ITER except a launcher. The RF power from the gyrotron is transmitted through evacuated corrugated waveguide and the CVD diamond torus window to the launcher. The RF beam is steered by movable mirrors and injected into plasma. The key points of EC system technology are 1) gyrotrons; 2) high efficiency and high power transmission; 3) fast and accurate scanning of RF beam direction to the plasma. On the first point, the performance of the gyrotron was proved as described in the previous section. However, when the gyrotron is operated in the EC system, where the several gyrotrons and other apparatus are simultaneously operated, some unexpected effects arise. As the power supply is converted from that of lower hybrid system, the voltage of the main power supply V_{main} is not regulated. The stabilized voltage of the accelerating DC Power Supply (APS), which determines the beam energy of the gyrotron V_b, guarantees the gyrotron operation itself. The voltage perturbation of the MPS appears on the retarding potential for the depressed collector V_{dp}. Here, $V_{dp}=V_b-V_{main}$. When eV_{dp} deeply exceeded the minimum energy of the spent beam, electron trapping becomes a problem. The electron trapping cause an increase of a leak current to the anode of MIG, which seems to be a cause of the trip of the power supply. In particular, it was frequent when the four gyrotrons start at same timing by a mutual coupling of the voltage perturbation. The influence of the voltage perturbation could be reduced by setting a ramp-up of the electron beam slow and V_{dp} lower. As a result, the simultaneous operation of four gyrotrons has been

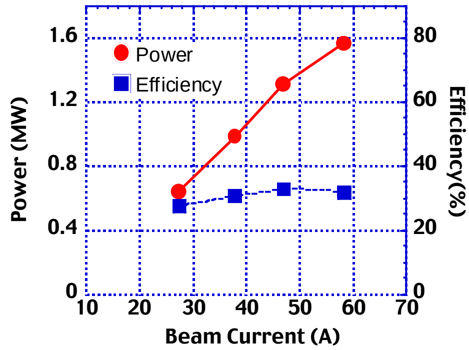


Fig.8: Beam current dependence of power and efficiency at 110GHz. Beam voltage is 84.5kV. Pulse duration is 1msec.

Table 1: Long pulse operation

Frequency (GHz)	Power (kW)	Duration (sec)
170	900	9.2
	750	17.
	500	30.
	450	47.
	300	60.
	200	132.
110	1300	1.2
	1200	4.1
	1000	5.

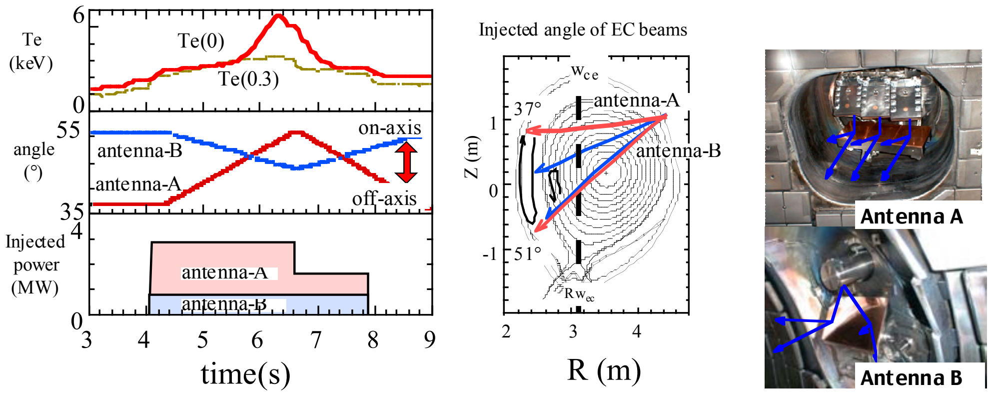


Fig.9: Real time control of electron temperature using antennas.

succeeded. For an EC system of many gyrotrons, stabilized main power supply voltage is desired to obtain a stable and high efficiency operation. Present issue for simultaneous operation is a trip of power supply caused by a noise from other apparatus.

On the second point, the coupling of the gyrotron output power with the waveguide was optimized by the careful adjustment of two mirrors in MOU, which is important for excitation of HE_{11} mode. And periodic sag of the waveguide has been minimized using the laser beam alignment technique. Present value of the transmission efficiency is ~80 %. The transmission line is composed of corrugated waveguide of 31.75mm in diameter, 7 miter bends and pair of polarizers are included. Total length is ~60m. The pressure inside the transmission line is kept in vacuum ~ $1x10^{-3}$ Pa, and a breakdown was not observed. The torus CVD diamond windows of 31.75mm and 60.5mm in aperture have shown a capability of stable 1 MW transmission. The performance of the launching system has been studied with two antennas for the last point. The dynamic beam steering capability was confirmed as shown in Fig. 9. Two antennas control the RF beam injection independently in a poloidal direction and the change of electron heating in the center is observed. The maximum central heating is obtained in case of the on-axis heating of antenna A. The maximum injection performance of approximately 3 MW for 2.7 s was achieved. As a result, the EC system contributed to realize high electron temperature plasma of 26keV [8], a suppression of neoclassical tearing mode [9] and current drive [10].

4. Concluding Remarks

The recent progresses of ECH technology development in JAERI are presented. The development of high power 170GHz and 110GHz gyrotrons has attained remarkable progress for ITER and JT-60U, respectively. At 170GHz, power outputs of 0.9MW/9.2sec, 0.75MW/17sec, 0.5MW/30sec, 0.45MW/47sec, 0.3MW/60sec, 0.2MW/133sec, etc have been demonstrated. And at 110GHz, 1.2MW/4.1sec, 1MW/5sec were obtained. These powers and pulse durations are limited by the temperature increase of the inner components, which was caused by the stray radiation from the built-in mode converter. The reduction of the stray radiation and the enhancement of cooling capability are essential for CW operation.

Using four 110GHz gyrotrons, the EC system is under operation on JT-60U. High power operation of the gyrotrons with simultaneous operation and high efficiency transmission enabled a 3MW/2.7sec injection. By the power deposition control using movable mirrors, the EC system contributed to the electron temperature of 26keV(n_e~$0.5x10^{13}cm^{-3}$), and the suppression of the neo-classical tearing mode. These results give a prospect for the ITER EC system.

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