Development of 100GHz Band High Power Gyrotron for Fusion Experimental Reactor

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Abstract In JAERI, 1MW gyrotrons of 170GHz and 110GHz are under development for ITER (International Thermonuclear Experimental Reactor) and JT-60U, respectively. Both gyrotrons have a depressed collector for an efficiency improvement and a low loss synthetic diamond window that enables Gaussian beam output over 1MW. Three 110GHz gyrotrons are used on an electron cyclotron heating and current drive(ECH/ECCD) system on JT-60U, in which the output power of ~0.8MW/3sec was generated from each gyrotron. As for 170GHz, output power of 1.2MW with electron beam of 85kV/49A was obtained on a short pulse gyrotron. The efficiency of ~57% was attained at 1.1MW with the depressed collector. Based on these results, the 1MW 170GHz gyrotron for long pulse operation was fabricated.

1. Introduction

Plasma heating and current drive by electron cyclotron wave (ECH/ECCD) is an attractive method from a view point of engineering on fusion experimental reactors. In ITER, 20-50MW/170GHz ECH/ECCD system is planed [1], where ECH/ECCD is expected as a tool of current drive and suppression of neoclassical tearing mode. The required power source is 170GHz/1MW/CW gyrotron. In JAERI, 100GHz-band high power gyrotron is under development for an application to ECH/ECCD system of ITER and JT-60U. After the first demonstration of 0.4MW/4sec with the efficiency of 50% by a depressed collector at 110GHz in 1994 [2], we started the development of 170GHz gyrotron as the R&D task of ITER/EDA (Engineering Design Activities). Although an output window was a major problem for 1MW output, this was solved by the success of the installation of the low loss synthetic diamond window on the gyrotron, where the power output of ~0.5MW/8sec at 170GHz was demonstrated [3].

Based on the results of 170GHz gyrotron, 110GHz 1MW gyrotron was developed for JT-60U. The 110GHz gyrotron will be applied to a plasma start-up in ITER, and ITER physics R&D on JT-60U, i.e., plasma heating, current drive and suppression of the neoclassical tearing mode, etc. In 1998, 1MW oscillation and high efficiency RF transmission were proved at 1MW/110GHz. First demonstration of plasma injection was performed using one gyrotron in 1999, and two more gyrotron systems were added in the system and simultaneous injection into the plasma was demonstrated with three gyrotrons in March 2000.

In parallel, the development of ITER gyrotron aiming 1MW/CW operation is continued under ITER/EDA extension. The problems to be solved were a stray RF in the gyrotron and an unwanted oscillation in the beam tunnel that sometimes caused an efficiency degradation. The countermeasure for these problems was included in the fabrication of 1MW gyrotron, and the experiment will start soon.

In section 2, the design of the 1MW gyrotron is summarized. In section 3 and 4, the results of 110GHz and 170GHz gyrotrons are described, respectively. In section 5, conclusion is given.

2. Design of 1MW gyrotron

A conceptional view of 1MW gyrotron is shown in Fig.1. Both 110GHz and 170GHz gyrotrons have a similar configuration. Total length is ~3m. The gyrotron consists of an electron gun, a cavity, a quasi-optical mode converter (a built-in RF launcher and phase correction mirrors), an output window and a collector. Inside of the gyrotron is kept in high vacuum; a base pressure is ~10^{-8}Pa. The gyrotron is installed in a super conducting magnet coil (SCM). The bore diameter of SCM is 240mm. The electron gun is triode type, which provide a hollow rotational electron beam of 70keV~90keV. An electron emitter is ring shaped metal coated barium oxide. The emitter is heated up to ~1250K by heater of ~200W. The electron beam is transported along the magnetic field to the cavity. By the mirror compression, a pitch factor (perpendicular velocity/parallel velocity) of ~1.2 is obtained at the cavity. The hollow electron beam (10.1mm and 9.13mm in radius for 110GHz and 170GHz, respectively) is injected into the cavity, where the best coupling between the oscillation mode and the electron beam is expected. A thickness of the electron beam is ~0.25mm. The RF power is generated in the cavity by a mechanism of electron cyclotron resonance maser(CRM). The oscillation mode is $TE_{22,6}$, and $TE_{31,8}$ for 110GHz and 170GHz respectively to suppress the heat deposition on the cavity wall by the Ohmic loss at ~ $2kW/cm^2$.

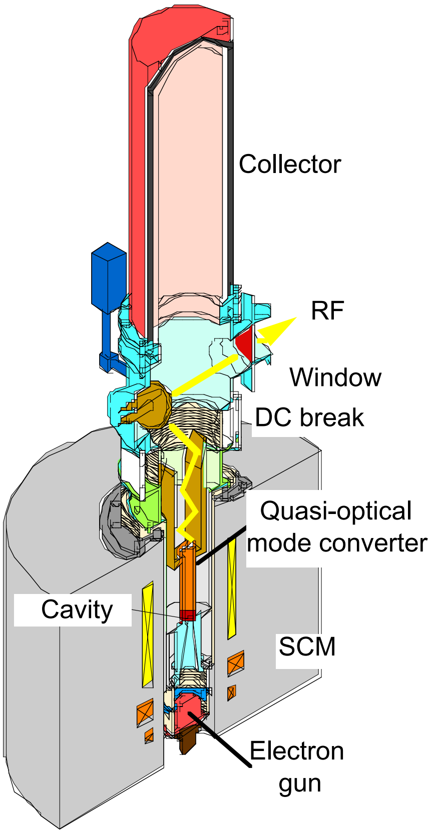


Fig.1 Conceptional view of gyrotron.

In the CRM interaction, there is a clear minimum energy in the spent electron beam that is determined from the gap between the RF frequency and the relativistic cyclotron frequency of the initial electron. And the rotational energy of the spent beam is converted to the paraxial energy at the downstream due to the conservation of adiabatic momentum. Because of these, an efficiency enhancement by the depressed collector is very effective. The efficiency enhancement factor is usually more than 1.7. In addition, large reduction of the collector heat dissipation and saving of the cooling water are expected, which is very important for a large system such like ITER. For the depressed collector operation, a ceramic cylinder is installed between the gyrotron body and the collector. The electron retarding voltage 30~40kV is applied at the ceramic.

The output window is the synthetic diamond. The large merit of the diamond window is that a Gaussian beam output is possible even at the multi-MW power level because of high thermal conductivity and low loss tangent. The oscillation RF is converted to Gaussian beam using a quasi-optical mode converter in the gyrotron. An aperture of the window is 80mm. As the loss tangent of the diamond is small ($\tan\delta \sim 2\mathrm{x}10^{-5}$), the temperature increase at the center is expected as 23K/45K for 110GHz/170GHz even in the 1 MW/CW transmission with such a concentrated beam. A matching optics unit (MOU) is connected to the gyrotron output window. The output power is focused using two mirrors in the MOU to couple with HE_{11} mode in the corrugated waveguide for long distance power transmission. Since the Gaussian beam is similar to HE_{11} mode in the corrugated waveguide that is used for a long distance power transmission, the complex surfaced phase correction mirrors can be avoided. Consequently, the coupling efficiency was significantly improved up to 95%, whereas that was substantially ~85% in the non Gaussian power output. Key components for long pulse operation, cavity, collector are cooled by water with flow rates of 100litter/min, 1200litter/min, respectively.

3. 110GHz Gyrotron for JT-60U

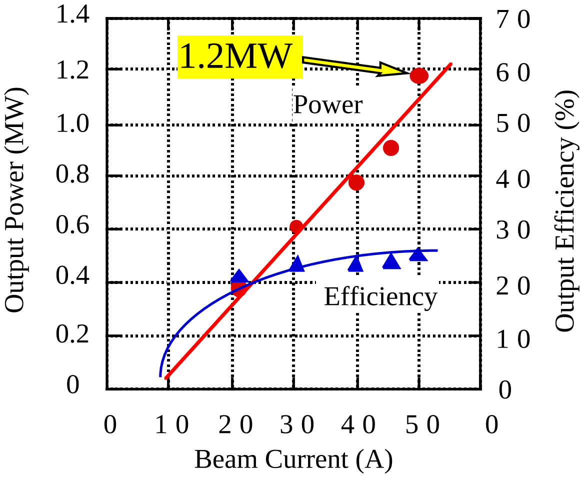
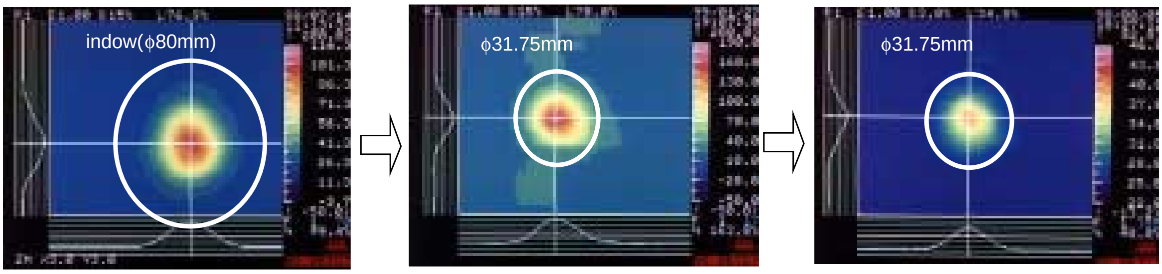


Fig.2 Beam current vs.power and efficiency at 110GHz.

In Fig.2, the beam current dependence of the power and the efficiency in the short pulse experiment (~1msec) is shown. Beam voltage is 85kV~90kV. Output power of 1.2MW was obtained. The efficiency is ~25%. Prior to the installation on JT-60U, the power transmission experiment was performed on the RF test stand at 1MW. Fig.3 (a), (b) and (c) show the power distributions measured by infrared camera at the output window, the input of the transmission line via MOU and the output of the transmission line, respectively. Here the transmission line is composed 40m of straight corrugated waveguide of 31.75mm in diameter which include the 8 bends. Two of the bends are polarizers and other two bends are directional couplers. Each configuration shows a clear Gaussain like power distribution. The transmitted power to the end of the transmission line is 84% of the gyrotron output power. This high efficiency was the result of the Gaussian beam output from the gyrotron.

In Fig.4 (a),(b) and (c), the time dependences of temperature of key components, cavity, collector, center of the diamond window, are shown. Here, the depressed collector voltage is 30kV. The cavity and the window stabilized after~1sec at the temperature increase of 60K and 25K, respectively. The cavity suffers a large heat load by Ohmic loss. The measured temperature increase by thermocouple was ~60K. This thermocouple was installed at 3mm from the inner wall of the cavity center, which indicates the surface temperature increase to be ~150K. This is in the acceptable level. The window temperature was measured by infrared camera (monitored wavelength is 3.5~5μm). The temperature increase by 25K agrees well with the design value. The collector temperature increase stabilized at ~6sec as expected in the operation of 0.5MW output. The perturbation on the temperature is due to the beam sweeping on the collector wall by the superimposed alternating magnetic field. These show that the key components of gyrotron permit 1MW/CW operation.



(a) (b) (c)

Fig.3 RF power profile measured by infrared camera. (a) Gyrotron window, (b) Input of transmission line, (c) output of transmission line after 40m transmission.

In Fig.5, a conceptional view of the ECH/ECCD system of JT-60U is shown. There are three independent gyrotron and transmission systems. The SCM is liquid helium free type. The output power couples with evacuated 31.75mm corrugated waveguide via MOU. The fast switching (~5μsec) of the power supply is done by IGBT (Insulated Gate Bipolar Transistor), which enables a crowbar free operation [4]. The plasma injection has started at March 2000, and as the initial result, 15keV of the electron temperature at the center plasma (average electron density of 0.6x10^{13}cm^{-3}) was obtained by simultaneous power injection with three gyrotrons [5].

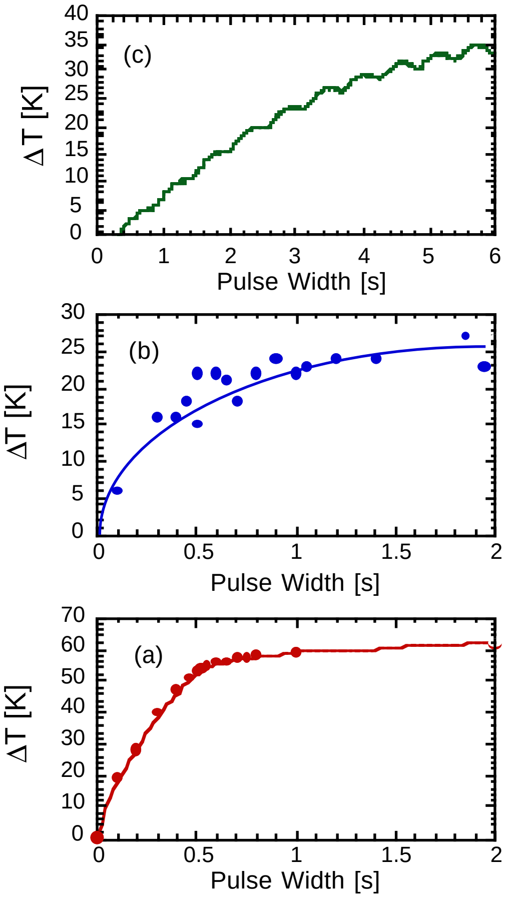


Fig.4 Time dependence of temperature increase of gyrotron components. (a) cavity, (b) window, (c) collector. Output power is 1MW for (a) and (b), and 0.5MW for (c). Depressed collector voltage is 30kV.

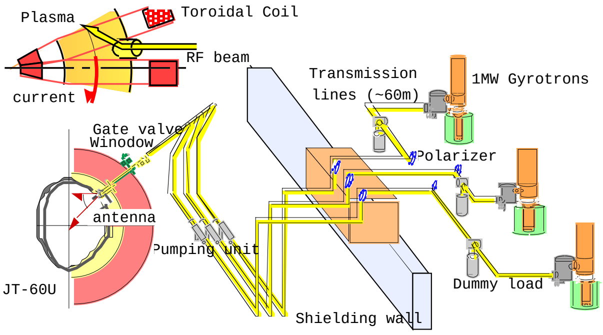


Fig5 Conceptional view of ECH/ECCD system on JT-60U.

4. 170 GHz gyrotron for ITER

The gyrotron efficiency decreases if the parasitic oscillation occurs in the drift tube between the electron gun and the cavity (beam tunnel), consequently the gyrotron performance is degraded due to the energy spread of the initial electron beam. In the previous experiment of 170GHz gyrotron in JAERI, the parasitic oscillation in the beam tunnel was sometimes observed. The frequency of the stray RF was lower than 170GHz. The stray RF leaked from the insulator ceramic of the electron gun. For example, ~25kW of leakage power (~143GHz) was observed at the electron beam of 85kV/40A. The gyrotron efficiency falls in the level of less than 25%, whereas the designed value was more than 30%. The beam tunnel was simple conical copper taper with the angle of 3.6deg. To suppress the parasitic oscillation, RF absorber (Silicon Carbide) was installed in the beam tunnel. At first, the new beam tunnel was tested in the short pulse gyrotron. This gyrotron has an essentially the same configuration with the long pulse gyrotron except the cooling capability. The Q-value of the cavity is 1530. In Fig.6, the beam current dependence of output power and efficiency is shown. The beam voltage is 72kV. The power increase linearly with the beam current. The output power of ~1.1MW was obtained at 46A/72kV. The oscillation efficiency was improved to 32% from 23% of no RF absorber. The efficiency was further enhanced to 57% at 1.1MW by the depressed collector of 31.5kV. The output power of 1.2MW was also obtained at the beam voltage of 85kV/49A. Throughout the experiment, no

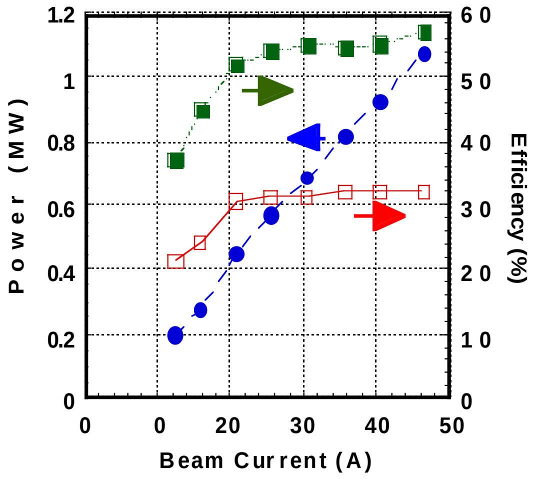


Fig.6 Beam current vs. power (closed circle), efficiency (open square), total efficiency with depressed collector (closed square). Beam voltage is 72kV, frequency is 170GHz.

evidence of the parasitic oscillation was observed. It was confirmed that the gyrotron efficiency significantly increase by the suppression of the unwanted oscillation in the beam tunnel.

Another issue is the countermeasure to the stray RF caused by a diffraction from the quasi-optical mode converter. This is supposed to be 5% of the oscillation power, i.e., 50kW with 1MW operation. As a countermeasure of the stray RF, we use the large insulator for depressed collector as a window of the stray RF. The ceramic is made of low loss tangent material, for instance silicon nitride or high purity aluminum oxide. At outside of the ceramic, the stray RF is absorbed. This configuration will avoid the temperature increase and outgassing at the inner wall of the gyrotron.

Based on the result of short pulse 170GHz gyrotron and 110GHz gyrotron, a high power gyrotron was fabricated aiming 1MW, long pulse operation. Fig.7 is a picture of the gyrotron. The pulse extension experiment will be performed.

5. Conclusion

In JAERI, 1MW gyrotron is under development for fusion experimental reactor. The 110GHz gyrotron is already under operation in ECH/ECCD system of JT-60U. This is the first demonstration of 1MW/multi-second level operation of the gyrotron in the ECH system with a depressed collector and a high efficiency long distance power transmission. It was shown that the temperature of the key components of the gyrotron, i.e., cavity, window, stabilized at 1MW level operation. The collector temperature also stabilized after 6sec as expected. After the demonstration of 0.5MW/8sec operation with the synthetic diamond window at 170GHz gyrotron, the short pulse gyrotron was fabricated and tested for efficiency improvement. By installing the RF absorber in the beam tunnel, the parasitic oscillation was suppressed. As a result, 1.1MW operation was obtained at the efficiency of 57%. Based on these results, 1MW/170GHz long pulse gyrotron was fabricated. The pulse extension will be done aiming 1MW CW (>60sec) operation.

Fig.7 Picture of 170GHz gyrotron.

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