DEVELOPMENT OF HIGH POWER LONG PULSE GYROTRON FOR ITER

K. SAKAMOTO, A. KASUGAI, M. TSUNEOKA, K. TAKAHASHI,
Yu. IKEDA, T. IMAI, T. KARIYA*, Y. MITSUNAKA*
RF Heating Lab., JAERI, Naka-machi, Ibaraki, 311-0193 Japan
*Electron Tube Division, Toshiba Co. Otawara-shi, Tochigi, 324-8550 Japan

Abstract

A development of 170GHz gyrotron has been carried out as a task of ITER/EDA, and remarkable progress was obtained. Critical issues on the gyrotron development; low efficiency, high heat load at the resonator, window problem, have been solved by breakthroughs; a depressed collector, 1MW single mode oscillation with a high order mode $TE_{31,8}$, and development of the diamond window gyrotron, respectively. The prototype ITER gyrotron which integrated these technologies were fabricated and tested. Up to now, the power output of 0.45MW, 8sec has been obtained with a diamond window gyrotron. These results give a clear prospect of the 1MW/CW 170GHz gyrotron.

1. INTRODUCTION

In ITER design, ECH/ECCD (electron cyclotron heating and current drive) is a major candidate for plasma heating, current drive and a profile control of ITER plasma. As a power source of ECH/ECCD system, 170GHz/1MW gyrotron was considered and its development was selected as a task of ITER R&D. JAERI (Japan Atomic Energy Research Institute) undertook the task, and has been carried out for five years. Before ITER/EDA project, no 170GHz gyrotron that can be applicable for plasma heating existed. There are three major problems to be solved for a development of ITER gyrotron. First one was the gyrotron efficiency was low, typically ~30 %, which pushed up the cost of ECH system. Second, there was no result of the stable 170GHz, 1MW oscillation with a reasonable efficiency using a CW relevant oscillation mode. Third, there was no output window that was applicable for ITER gyrotron. However, these difficulties must be overcome during ITER gyrotron, and extensive studies have been carried out to obtain these solutions. As a result, several breakthrough technologies have been achieved during the ITER/EDA period. This paper describes these innovative R&D results.

In section 2, these key technologies which were developed by JAERI during ITER/EDA are described. In section 3, the experimental result of diamond window gyrotron with a depressed collector is presented. In section 4, conclusion is given.

2. BREAKTHROUGHS DURING ITER/EDA

2.1 Depressed Collector [1]

An energy recovery of a spent electron beam is indispensable to improve the efficiency of the gyrotron. As shown in Fig.1, a rotational electron beam is accelerated at an electron gun (MIG) using a beam accelerating power supply, which need only a small capacity (~80kV x <0.3A). The power is supplied by a main power supply at the voltage of 50 kV [1,2]. After the interaction with RF (electron cyclotron resonance maser) in a resonator (cavity), the spent beam is decelerated by a retarding potential between the resonator potential and the grounded, which is equivalent to the energy recovery to the power supply. As a result, the original efficiency was improved up to 50% with the depressed collector voltage of 30kV. An oscillated RF is converted from the waveguide mode to the RF beam with a quasi-optical mode converter. In the experiment, the output power of 0.4 MW with pulse duration of 4 sec. was obtained. The maximum efficiency obtained in the series of the experiment was 58 %.

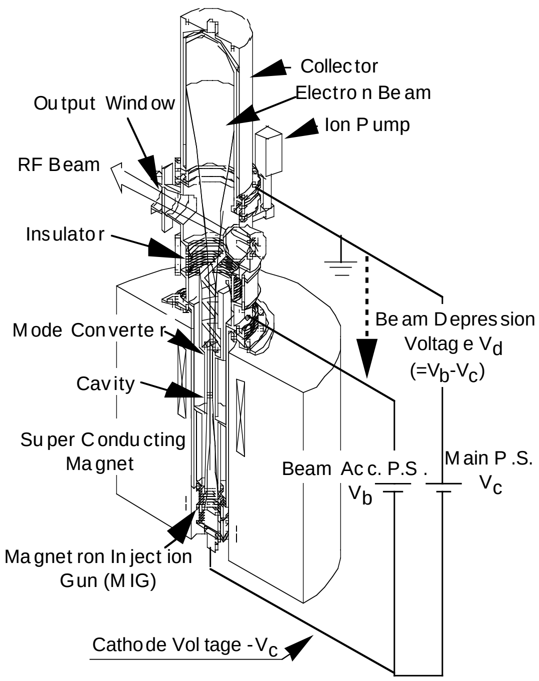

Fig.1 Conceptional view of the depressed collector gyrotron and the power supply system.

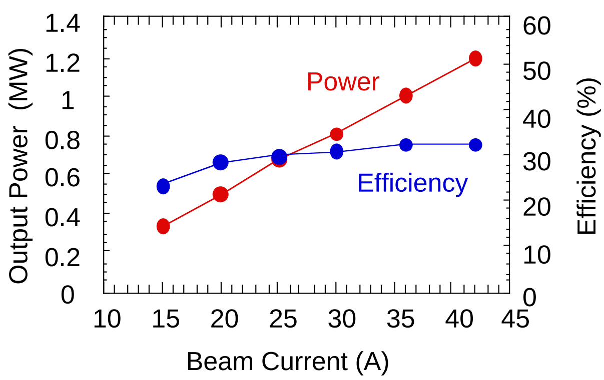

Fig.2 Beam current dependence of output power and efficiency at $TE_{31,8}$ mode. Beam voltage is 88kV. Frequency is 170GHz.

The depressed collector is very important both for the gyrotron itself and ECH system. The collector heat load, which was one of critical issues of the long pulse gyrotron, can be reduced to ~40 %. For ECH system, the capacity and the voltage of the main power supply are reduced to ~1/2, and a cooling system can be reduced ~1/3 of the conventional system [2]. These significantly contribute to the reduction both of the initial and the running costs of the ECH system.

2.2 Stable oscillation of 170 GHz/1MW with high order mode [3]

Generally, a heat load on the resonator wall by the ohmic loss increases in proportion to $f^{2.5}$. Here, f is a frequency. The oscillation modes, which has been established in the lower frequency gyrotron such as $TE_{22,6}$ cannot be used for 170GHz/1MW gyrotron. Therefore, much higher mode, e.g., $TE_{31,8}$ (508th higher mode), has to be adopted to reduce the heat load within an acceptable level ~2 kW/cm^2. On the other hand, such modes have very complex configuration and have many competing modes during the power growth. In the oscillation design, we selected relatively low pitch factor α (=rotational velocity/axial velocity) electron beam, α=1.0~1.1 to avoid an instability of the electron beam. For the resonator, the high Q-factor one, which had long interaction length, was used to cope with the low pitch factor beam. The oscillation efficiency is not so high with low pitch factor beam, but this can be compensated by higher energy recovering ratio with the depressed collector. As a result, more than 50% of the overall efficiency is expected. The oscillation test of $TE_{31,8}$ was done using short pulse gyrotrons which had the high Q-factor resonators (Q=1700~2400). In Fig.2, the beam dependence I_b of the output power and the efficiency is shown. The excited mode was $TE_{31,8}$. Here Q~1700. A beam voltage was 88kV. The power was ~1.2MW at I_b=42A. Then the oscillation efficiency was 32.4%, which agreed well with the calculation.

2.3 Diamond window

Most recent breakthrough was the development of the diamond window. According to the result of **2.2**, the long pulse gyrotron was developed. As a window material, a sapphire, silicon nitride was used. In Fig.3, the temperature increase of the silicon nitride window is shown with triangles. The window surface was cooled by fluorinert with a double disk configuration. The window temperature exceeded 150 deg.C after 0.8 sec at 0.5MW penetration because of the large dielectric loss of the window material. It was concluded that the long pulse operation was possible only below 170 kW for conventional window. Owing to the recent progress of the synthetic diamond, however, the large disks that can be utilized to the gyrotron window begin to be supplied from the industry [4]. Under the ITER collaboration, JAERI, FZK and DeBeers performed the development of the diamond window [5]. It was confirmed that the diamond has extremely high thermal conductivity (~1800W/mK), and low loss tangent. By utilizing the excellent properties, we designed an edge cooled single disk window. Coolant is water. After the success of brazing with metal cuffs, the window assembly was successfully fabricated. In Fig.4 (a), the picture of the diamond window assembly is shown. The window aperture is 83 mm, the thickness of the disk is 2.23 mm which corresponds to 3 wavelengths in the diamond. The high power penetration experiment at 170GHz/110kW/10 sec. proved its outstanding properties, and the temperature increase agreed well with the prediction [6].

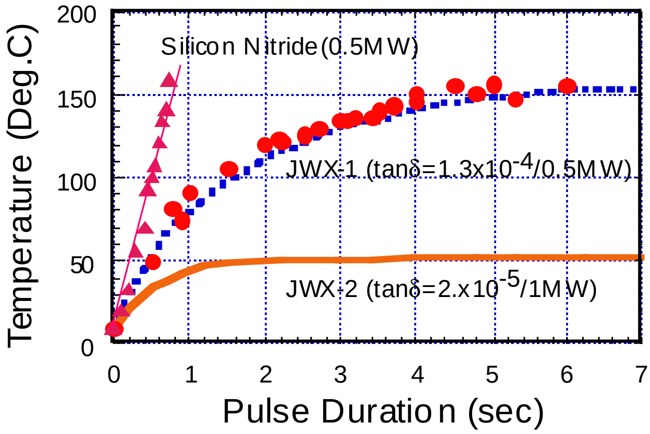

Fig.3 Time dependence of temperature of the Diamond window (JWX-1,2) and Silicon Nitride. Closed circles and triangles are experimental data of JWX-1 and Silicon Nitride window respectively.

(a)

(b)

Fig.4 (a) Picture of diamond window assembly. Aperture is 83mm. Thickness of disk is 2.23mm.
(b) 170GHz gyrotron with diamond window installed in the JAERI gyrotron test stand.

3. DEVELOPMENT OF 170GHz GYROTRON WITH DIAMOND WINDOW

After the success of the power transmission experiment, the diamond window was installed on the 170 GHz long pulse gyrotron. Key design parameters of the long pulse gyrotron that integrated the breakthrough technologies described in Section 2 are listed in table 1. The window stood the one-week baking at the temperature of 450 deg.C that was necessary in the fabrication process of the gyrotron, and good vacuum was obtained (less than $1x10^{-8}$ Pa). In Fig.4 (b), a picture of the diamond window gyrotron that was installed on the JAERI test stand is shown. Output power had fairly flat profile to avoid the power concentration. This profile was reformed to that of HE_{11} mode of the corrugated waveguide (88.9mm in diameter)

Table 1 Gyrotron deisgn parameters

Frequency	170GHz
Beam voltage/current	80kV/45A
Pitch factor	~1.0
Q-value	2400
Output power	1MW
Total efficiency	50%
Energy recovery factor	2
Pulse duration	CW
Output mode (window)	Flat beam
Mode converter	In-waveguide
Window	Diamond
Length	~3m
Weight	~650kg

using two phase correction mirrors in the matching optics unit. The output power was measured by temperature increase of the cooling water of the RF dummy load calorimetrically, and the RF waveform was monitored by a miter bend typed directional coupler.

Pulse extension experiment was done at the beam voltage of 84 kV, the depressed collector voltage of 32 kV, and the beam current of 31 A. The output power is 0.52 MW with pulse duration of 6.2 sec. The oscillation was very stable. The window temperature was monitored by an infrared camera (measurement wavelength was 3-5.4 μm). Other temperatures were monitored by thermocouples. The temperatures stabilized within 6 sec. In Fig.3, the experimental data of temperature increase of the first diamond window (JWX-1) are shown with closed circles. The dotted curve is a simulation result with $\tan\delta=1.3\times10^{-4}$ and 0.5MW output in a flat power profile. Since the loss tangent of the used diamond was relatively high, the window temperature stabilized at 150 deg.C. However, no trouble such as an arcing was found. No change occurred on the diamond quality with the one week baking at 450deg.C. Up to now, maximum output energy of 3.6 MJ (0.45 MW, 8 sec) has been obtained. Total number of the operation of greater than 1 sec was ~1300. Total penetration energy was ~1.8 GJ. After the experiment, the surface of the diamond disk was inspected, but no damage was found.

We already fabricated the second window (JWX-2) using a disk of $\tan\delta$~2×10^{-5}. In Fig.3, the temperature increase of JWX-2 is shown with solid line. Here, the output power is 1MW with a Gaussian profile. The temperature increase is less than 50 deg.C with 1MW output. This suggests the window of multi-megawatts transmission is well possible. It is concluded that the synthetic diamond disk is a reliable, and gives the solution to the window problem, which has been the most annoying issue for ECH technology.

4. CONCLUSION

During ITER/EDA, the development of 170GHz gyrotron has remarkably progressed. The most critical problems of the 170 GHz gyrotron were low efficiency, large heat deposition on the resonator, and the output window. However, depressed collector, success of single mode oscillation of high order mode and the diamond window, which have been performed by JAERI, have solved these difficulties. It is concluded that the key issues for development of 170GHz, 1MW long pulse gyrotron were almost overcome. The demonstration of the CW operation at 1MW will be tried in near future, and the performance of the diamond window gives the positive outlook for the power enhancement per a tube that contributes to further cost reduction of ECH system.

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