Development of high power gyrotron and EC technologies for ITER

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Abstract. The development of a high power 170 GHz gyrotron is underway in Japan Atomic Energy Agency (JAEA) for electron cyclotron heating and current drive system (EC H&CD) on ITER. On the reliability test as a simulation of ITER operation, a repetitive power generation of 800 kW / 600 s at an electrical efficiency of 52-57 % was performed with the interval of 20-30min for 8 days. No damage was found on the gyrotron after the test. This gives a clear prospect that the EC system works on ITER. Next, for the neo-classical tearing mode (NTM) suppression, 5 kHz-full power modulation was demonstrated with pulse duration of 60 s. For this purpose, a full beam current modulation was adopted to minimize the collector heat load using the anode voltage switching of the triode type electron gun. Furthermore, on the dual frequency gyrotron development, the 1.3 MW oscillations at 170 GHz and 136.8 GHz were successfully demonstrated at short pulse operation. Here, both a position and a pitch factor of the electron beam in the cavity was optimized using the anode voltage control.

1. Introduction

On ITER, 20MW of Electron Cyclotron (EC) system is planned [1-3]. Main roles of the electron cyclotron heating and current drive system (EC H&CD) are plasma initiation, volt-sec saving in the plasma start-up phase, plasma heating for the ignition and off-axis CD to control the neo-classical tearing mode (NTM). The Japan Domestic Agency (JADA) procures eight 1MW-170GHz gyrotrons and one equatorial launcher. On the R&D in JADA, a basic specification for ITER was satisfied at 170 GHz gyrotron, i.e., 1MW, 800 s 55 % in 2006 [4,5]. This gyrotron employs a triode type magnetron injection gun that uses a beam voltage of ~70kV and electron beam current of ~40 A to generate 1MW output at 170GHz. The oscillation mode is $TE_{31,8}$ in a cylindrical resonator, which is converted to Gaussian like beam and output through the edge cooled single disk diamond window. The RF beam is introduced to the corrugated waveguide of 63.5mm diameter via a matching optics unit consist of two-phase correlation mirrors. The RF power is transmitted to the 1 MW dummy load and absorbed here. The gyrotron outputted power is measured calorimetrically. Using this gyrotron, extended experiments for ITER procurement are carried out, such as a gyrotron reliability test, and high frequency power modulation up to 5 kHz in CW-mode. In addition, developments of the ITER transmission line components [6] and launcher mm wave components [7] have been conducted using the gyrotron as a power source. These provide important database for design and construction of ITER EC H&CD system. In parallel, a development of dual-frequency gyrotron is underway for a future advanced EC H&CD system. This dual-frequency gyrotron will give a large flexibility to the EC H&CD experiments.

In this paper, present activities of the gyrotron development in JAEA are presented. In section 2, the result of the gyrotron reliability test for RF generation is described. In section 3, the result of the development of high frequency power modulation in CW operation is presented. In section 4, the development of the dual-frequency gyrotron is presented. The summary is given in section 5.

2. Gyrotron reliability for ITER application

The reliability of the gyrotron is highly important for ITER application. The reliability is tested by the the repetitive power generation which simulates the ITER operation. First demonstration of the repetitive operation has been conducted in 2008. Then, the 10 pulses of 0.8 MW-400 s have been successfully generated in series at every 30 min [8]. As a next campaign, here, the repetitive operation of 0.8 MW-600 s shots were performed with an interval of 20~30 min. The total shots are more than 100 shots to obtain a statistical data. The electrical efficiency of each shot was in the 52 %-57 %. In Fig.1, the time history of the repetitive operation represented by the beam curent of the gyrotron is shown. After the morning conditioning shots, the repetitive operation was carried out in the afrernoon for 8-days. In Fig.2, the summation of the pulse duration of shots is shown. The 88 shots are accounted as a denomenator, and 72 shots was very stable 600 s operation, i.e., the success rate of 600 s shot was 82 % [9]. Rest of the shots are terminated during the shot by the

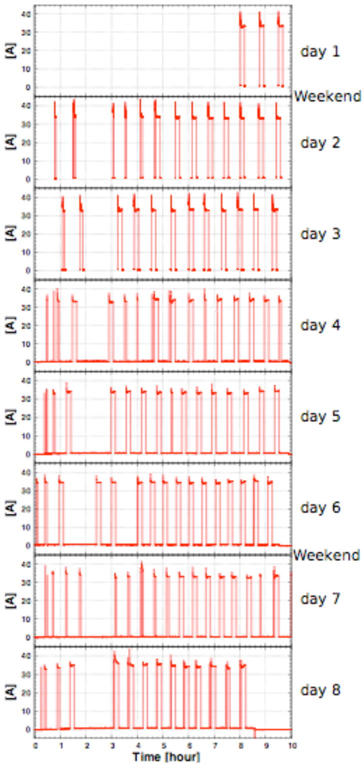

Fig.1 Shots of repetitive operation test. Vertical axis is the beam current of the gyrotron. Generation power is ~0.8MW.

interlock. Reasons of the pulse termination are a photo-intensity increase measured by a photo-multiplier through the viewing port, sudden increase of the beam current, etc. One cause of the photo-signal increase is the mode transition resulting in the RF scattering in the tube. Fig.3 is the transition of the ion pump current corresponding to the gyrotron vacuum pressure. The pressure increases by the power generation, however, the pressure returned to the original level soon after the shot and no influence gives to the following shots. The base pressure decerased shot by shot. Here, it should be pointed out that a finite level of the base pressure, ~1x10^{-5} Pa, existed througout the test. A pin hole leak was identified after the test at the ion pump section. This pin hole was fixed by the Vacseal® and the ion pump current turned to ~0 μA. It is considered that this level resisual gas does not cause a major problem on the gyrtorn operation. As a tentative conclusion, the gyrotron is reliable for ITER experiment. To increase the operation ratio further, the employment of the quick recovery system during the shot will be effective in addition to the effort to reduce the interlock-event frequency.

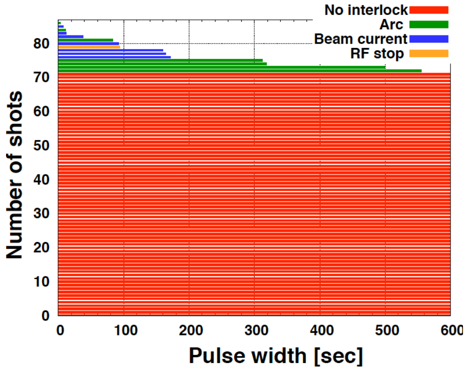

Fig.2 Summary of pulse duration of repetitive operation at 0.8 MW.
The interval of each shot is 20-30 min.

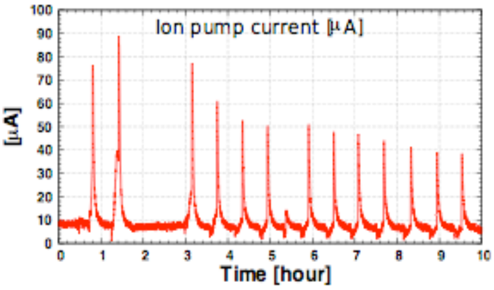

Fig.3 Transition of the ion pump current corresponding to the vacuum pressure in the gyrotron by the RF power generation. Output power is 0.8 MW.

3. High Frequency Power Modulation

For the neo-classical-tearing (NTM) mode suppression, high frequency power modulation with the pulse duration of ~1min is required. However, the modulation period is limited by ~1 s at most of the present-day NTM suppression experiments. Generally, the conventional modulation method causes large power consumption at the gyrotron collector or at the

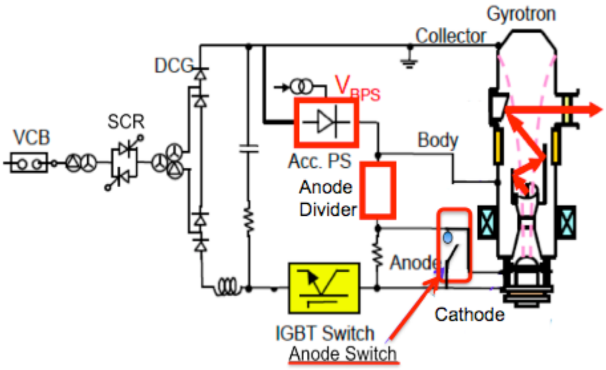

Fig.4 Configuration of power supply and gyrotron with triode electron gun.

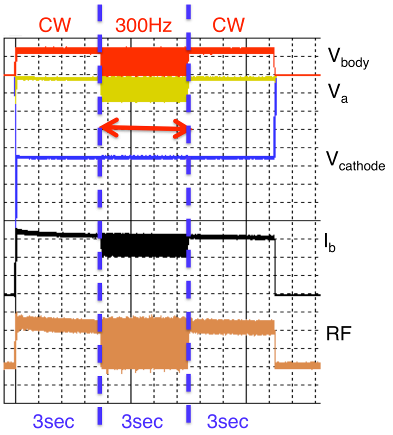

Fig.5(a) Power modulation at 300 Hz with BPS voltage modulation. Output power is ~0.6 MW.

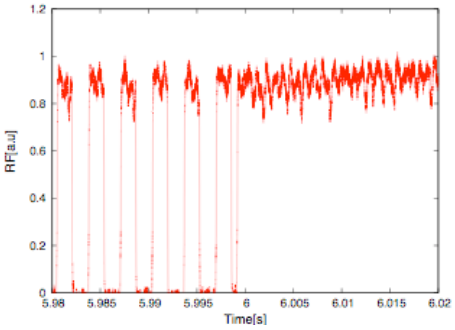

Fig.5(b) Time expansion of RF power modulation-CW phase.

power supply system. So, the extension of the pulse duration has been the issue for ITER application. A present reference design for ITER is that the full current modulation is expected up to 1 kHz and a half power modulation at 5 kHz to avoid the large heat deposition to the collector. It is anticipated that the half power injection to the x-point of the magnetic island degrades the performance of the NTM suppression. Here, we demonstrate the full power modulation is possible at 5 kHz by using an anode voltage switch of the triode electron gun. In Fig.4, the gyrotron and the power supply configuration of the JAEA test stand is shown. The JAEA gyrotron is featured by the triode electron gun. The body voltage V_{body}, which is equivalent to the depressed collector voltage V_{dep}, is fed by the body power supply (BPS). The anode voltage V_a is controlled to change a pitch factor of the electron beam independently with the beam acceleration voltage V_b. In addition, as the beam extraction voltage V_{ak} ($=V_{cathode}-V_a$) decreases the beam current I_b does, and the I_b go to 0 A at $V_{ak}=0$. This indicates that the feature of the triode MIG is preferable for the power modulation with the beam current modulation [10], which results in lower heat load at the collector.

Fig.5 (a) is an example of the power modulation at 300 Hz carried out by using the ITER-relevant BPS alone. Pulse duration is 9 sec, and 3 sec-300 Hz BPS voltage modulation V_{body}=0~23 kV was tried in the middle phase of the pulse. Fig.5 (b) is a time expansion of the output power which indicates the RF power changes from the modulation phase to CW one. This is a demonstration of the gyrotron operation for the NTM control, when the power modulation is required suddenly during the shot. The V_{ak} changes with the V_{body} modulation. The beam current and the mm wave power are modulated I_b=20A-30A and P_{RF}=0-0.6 MW by V_{body}=0-23 kV, respectively. As the beam current drops 2/3 in the non-oscillation phase, the collector heat load is mitigated. However, when the modulation frequency increases, the V_{ak} could not follow because of the slow time constant of the circuit. Fig.6 is a result of 5 kHz BPS modulation. The full RF power modulation is realized because of a mismatch of the oscillation condition in the non-oscillation phase. However, the change of the beam current is small and consequently the collector heat load becomes large.

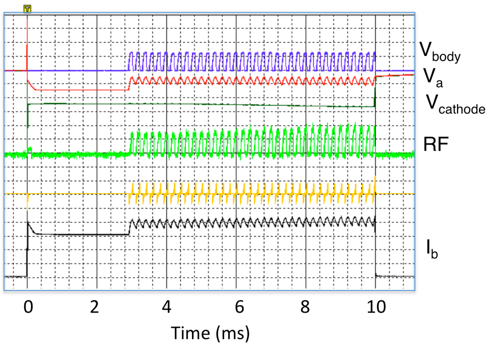

Fig.6 Power modulation at 5 kHz with BPS voltage modulation.

Fig.7 Appearance of the anode switch. $1.1\text{m}^W \text{x} 1.0\text{m}^L \text{x} 0.8\text{m}^H$.

To realize the power modulation with full beam current modulation, an anode switch composed of IGBT's (Insulated Gate Bipolar Transistor) is proposed and tested. The anode switch makes short-circuit between the cathode and anode resulting in the beam current termination. Fig.7 is a picture of the anode switch which is placed near the gyrotron to minimize the cable capacitance minimum. Fig.8 is an example of the 5 kHz full beam current and power modulation for 60 s at the output power of ~1.1 MW. Here, V_{body}~24.3 kV, $V_{cathode}$~-45.2 kV (main power supply voltage) and $I_{beam} \geq 50$ A. As the beam current goes to zero, the heat load on the collector is significantly decreased. Furthermore, the main power supply and the body power supply are in CW operation; consequently, the beam energy keeps a high stability, which brings about stable RF oscillation. It is concluded that the anode switching is very simple and effective for CW power modulation.

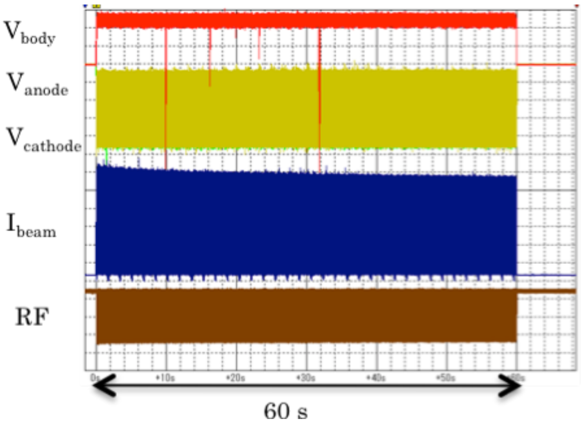

Fig.8 Experimental result of 5 kHz power modulation. Pulse duration is 60 s.

Fig.9 Picture of dual frequency gyrotron.

4. Dual frequency gyrotron

A development of a dual-frequency gyrotron is underway for a future advanced EC H&CD system. Fig.9 is a picture of the dual frequency gyrotron. The design was made to satisfy the matching condition at the output window and to have a similar radiation angle from the window for both frequencies, and the modes of $TE_{31,11}$ and $TE_{25,9}$ are selected, which have frequencies of 170 GHz and 136.8 GHz, respectively. The oscillation is obtained by setting a proper magnetic field at the cavity (cavity filed). The optimum beam radius at the cavity is selected by setting a proper mirror ratio between the cavity field and MIG field. A pitch factor of the beam can be optimized by setting V_{ak} independently with the beam voltage. In Fig.10, the initial result of the beam current dependence of the output power and the oscillation efficiency is shown at short pulse operation (~0.5 ms). Up to now, the output power of 1.3 MW was obtained. And, 1 MW with efficiency of more than 30 % was also achieved for both frequencies.

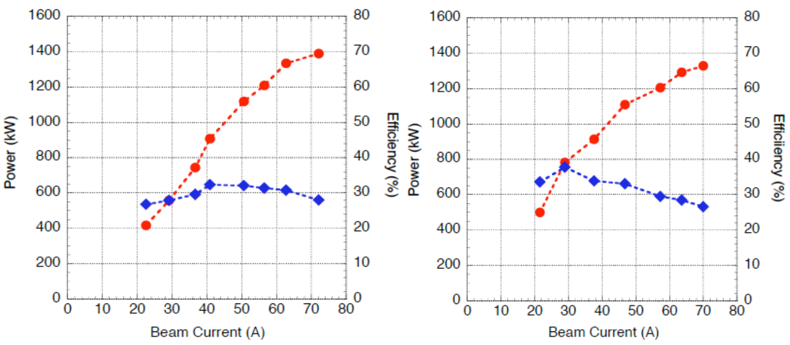

Fig.10 Beam current dependence of output power and efficiency without depressed collector at short pulse (~0.5ms).

(left) 170 GHz. V_b=71~72 kV (right) 136.8 GHz. V_b= 68~69 kV.

5. Summary

A progress of the ITER gyrotron development was described. For the ITER relevant operation, the 800kW/600s power generation was repeated for every ~30min. Temperature of all parts stabilized during the shot. High vacuum was kept during shot and returned to the original level by the next shot, and no influence is given to the following shots. The result indicates the gyrotron is robust for the hard ITER operation. Another activity is the 5 kHz CW-relevant power modulation, which is inevitable for the NTM suppression of ITER plasma. Here, the anode switching of the triode type electron gun was adopted. Since the beam current is suppressed to zero during the non-oscillation phase, the collector heat load is significantly reduced. As a result, stable 1.1 MW level 5kHz power-modulation was demonstrated with full beam current modulation. Furthermore, this method has advantage that the gyrotron oscillation is stable because the beam voltage of is kept constant. Finally, for the advanced EC H&CD system, the dual frequency gyrotron with the triode MIG is developed and the preliminary results are performed. By controlling the anode voltage, the optimum oscillation condition is obtained for both frequencies by fixing the beam voltage constant. This will make the EC H&CD system more attractive for fusion application.

Acknowledgement

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