Development of Long Pulse and High Power 170GHz Gyrotron

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Abstract. Recent activities on the research and development of 170 GHz gyrotron were presented. In the 170 GHz gyrotron experiment in JAERI, pulse duration had been limited by the beam current decrease due to the emission cooling of the electron emitter. A pre-programming control of the heater power was introduced to keep the beam current constant and to avoid the oscillation mode shift to a lower mode during the operation. And, a built-in mode converter system was improved to reduce the stray radiation. In the preliminary experiment results of 0.2 MW/480 sec and 0.13 MW/600 sec were obtained. The pulse extension experiment at higher power will be followed. In parallel, a study of the high order mode oscillation was carried out using a short pulse gyrotron (~1 msec). The oscillation mode is TE_{31,12}, which allows 1.5MW level CW operation. A stable oscillation of TE_{31,12} was demonstrated at the power of 1.56 MW. The maximum efficiency was 30% at 1MW output. This result indicates that the high order mode up to the level of TE_{31,12} will be acceptable to increase the power or to reduce the heat load on the cavity wall at 1MW output.

1. Introduction

In ITER (International Thermonuclear Experimental Reactor) project, a 20-40 MW of the electron cyclotron (EC) system is planned for a heating (ECH) to ignition, current drive (ECCD) and plasma stabilization [1]. As a power source of ECH/ECCD system, the development of 1 MW 170 GHz gyrotron has been carried out. Key technologies for the ITER gyrotron such as a diamond window [2-5], a depressed collector for high efficiency operation [6] and a stable operation at 170 GHz/1 MW with higher mode [7-8], have been developed. Next issue is a demonstration of long pulse operation. Up to now, experimental results of 0.5 MW/100 sec and 0.9 MW/9.2 sec were demonstrated in JAERI [9,10]. For further pulse extension at high power, some modifications were carried out. One problem was large beam current decrease due to so called the emission cooling of a cathode. During the operation, the oscillation mode shift from TE_{31,8} to TE_{30,8} was caused by the current decrease. Then, the magnetic field of the cavity should be increased to avoid the downshift of the oscillation mode, however, the efficiency decreases and the parasitic oscillation in a quasi-optical mode converter appears. Another issue was stray radiation of 8-10% of the output power. Though no critical influence of the stray radiation was observed to attain the 100 sec operation, the stray radiation should be suppressed as much as possible to avoid the risk of damage of inner components, in particular the ceramic parts, and to minimize the capacity of the cooling system. In parallel, we initiated the study of oscillation at higher order volume mode. In the present design of the ITER gyrotron, the oscillation mode TE_{31,8} was adopted according to the design before 1994. The peak heat load of this mode is a level of 2 kW/cm^2, which is acceptable, but the cavity has small margin for power increase over 1MW.
As the 1 MW oscillation has been proved by the development up to now, it is interesting to try the oscillation with the high order mode in a simple cylindrical cavity to decrease the heat load, although an anxiety arise that the stable operation may be prevented by the mode competition problem. In this paper, we report recent activities on the development of 170 GHz gyrotron for ITER and the study of the high order oscillation mode for a future advanced gyrotron.

2. 170GHz gyrotron and long pulse operation

2.1 Present status and improvement for long pulse operation

The oscillation mode is TE_{31,8} of a cylindrical cavity. A Q-factor of the cavity is 1530. The oscillation power in TE_{31,8} mode is converted to a Gaussian beam by a quasi-optical mode converter and outputted through an edge cooled diamond window. The aperture of the window is 80mm. The loss tangent of the diamond disk is 2\times10^{-5}. By edge water-cooling, the temperature rise of the disk center stabilizes at ΔT=45 °C (0.9 MW transmission). A gyrotron experiment was carried out in a RF test stand (RFTS) with a depressed collector operation. Due to diffraction loss of the quasi-optical mode converter, the calculation shows that ~6% of the oscillation power scatters in the gyrotron. The pulse extension experiment was performed at the output power of ~0.5 MW level up to 100 sec. The temperature of key components was stabilized during the shot. The outgas level was as low as ~10^{-5} Pa. The stray radiation is extracted from a sub-window and a ceramic insulator (DC break made of Si₃N₄ cylinder) installed for the depressed collector operation. In the experiment, absorbed stray radiation at the outside of the gyrotron was ~8% of the output power. The DC break is cooled by fluorinert. A Silicon Carbide (SiC) cylinders are installed in the beam tunnel in order to suppress the parasitic oscillation.

The pulse was extended up to 100 sec at 0.5 MW. Beam voltage was 71.5 kV. Then, the beam current decrease was observed from 35 A to 25 A due to the emission cooling, which is accompanied with the output RF power drop from ~560 kW to ~440 kW. One method to compensate the current decrease is to boost the heater power of the electron gun. By introduction of a pre-programming control of the heater input power, constant beam current was obtained at 27 A for 1000 sec. In a radiator used in the present gyrotron, ~3 % of the radiated power could not enter into the first mirror. To reduce the diffraction loss, the radiator was designed using CCR-Surf3D and LOT codes [11,12]. The radiator has a taper of 0.2 degree and the diameter of output is 43 mm. The 99.5 % of the radiated power will enter into the first mirror. At the end of the radiator, the power ratio of the original mode, TE_{31,8}, is 21.9 % of the input power. The output power from the radiator is tailored to a parallel beam by a parabolic mirror, and the beam profile is reformed to the Gaussian beam by using two mirrors with phase correction.
2.2 Experimental results

The RF beam pattern was measured by an infrared (IR) camera. The temperature increase of the paper placed on the output window was monitored at the pulse duration ~0.4msec. In Fig.1 (a) and (b), the designed power profile (linear scale) and the measured one are shown, respectively. The experiment shows an elliptic form, which is different from the designed circular profile. The reason is not identified yet, but this is may be caused by an error in the fabrication process of the radiator. The output power is designed to couple with HE$_{11}$ mode of a corrugated waveguide via two mirrors in a matching optics unit (MOU) with the efficiency of 98.5%. However, a generation of stray radiation is anticipated in the MOU due to the unexpected power profile. The pulse extension experiment was carried out using a water load directly connected to the gyrotron output to inspect the characteristics of the long pulse operation, as a first step. The RF power is absorbed by water in Teflon tube. The power is monitored by the temperature increase of the water. A flow rate of the water is 200 litters/min. The dummy load is evacuated to avoid the RF breakdown. The pulse extension was carried out at less than 200 kW, which is limited by the capacity of the dummy load. In the initial stage of conditioning (a few second level), a spark in the gyrotron was sometimes observed through the viewing port as shown in Fig.2. The cause of the spark is not clear, but it seems a small metal tip is heated by the stray RF and peeled away from the wall. Then, abrupt outgassing is accompanied. Such sparks must be one of the causes of outgassing in the conditioning process of electron tubes. The spark disappeared soon after the conditioning shots, and then the pulse length is extended without trouble. In Fig.3, the waveforms of applied voltages, beam current, signal of photo-multiplier (arcing), vacuums, and the output power at 10 min operation are shown. The current keeps a constant value by the pre-programming control of the heater power. Consequently, the output power measured by temperature of cooling water was stable and constant during 10 min. The vacuum in the tube was the order of the $10^{-6}$ Pa, and no arcing was observed. At 200 kW, the pulse duration was extended up to 480 sec. The temperature increase over 100°C was observed at a few spot area of the gyrotron body due to the stray radiation, where the cooling was insufficient. This section has positive high potential for the depressed collector and is covered by a MC nylon cylinder for insulation. As the insulation resistance of the MC nylon degrades at higher temperature, the further pulse extension was halted. The cooling for these parts is enhanced from the outside of the gyrotron.
The profiles of output beam were measured at some distances and the phase distribution was analyzed. Using the data of output beam, two phase-correction mirrors in the MOU are fabricated to obtain a good coupling with the corrugated waveguide that leads the power to 1MW/CW dummy load. The pulse extension experiment at higher power will be re-started using the revised MOU system.

3. Experiment of high order oscillation at $TE_{31,12}$ with short pulse gyrotron
A short pulse gyrotron was designed and fabricated for a study of high order mode oscillation. The operation mode is $TE_{31,12}$, and its Q-factor is $\sim 1660$. The length of the straight section of the cavity is 10.5 mm which has up- and down-tapers of R=70 mm for both sides. The diameter of the cavity at straight section is 43.66 mm. The peak heat load on the cavity wall is 1.8 kW/cm$^2$ at the oscillation power of 1.5 MW. The inner configuration of the gyrotron is shown in Fig.4. The operation is done using a SCM (super conducting magnet) of the long pulse 170GHz gyrotron. A configuration of a magnetron injection gun is the same with that of 170GHz/$TE_{31,8}$ gyrotron since the beam diameter in the cavities are 18.26 mm for both modes. The oscillation mode is converted to beam mode using a radiator and a parabolic mirror. Using two additional mirrors, the power is extracted through the window obliquely. The power profile is shown in Fig.5. The designed power profile is indicated in contours for every 10% of the peak power. The measured one by IR camera is shown in colour. Almost perfect agreement was obtained between them. A frequency is 170GHz. These indicate the oscillation mode is $TE_{31,12}$, and the radiator works well at high order volume mode. As no phase correlation is adopted on the mirror surfaces, the output profile is non-circle. The transmission efficiency from the cavity to the window is 93.3 % in calculation, which can be increased furthermore by optimizing the mirror surfaces. The RF power is measured calorimetrically by a dummy load made of silicon carbide. In Fig.6, the electron beam current dependence of the output power and the efficiency is shown. The pulse duration is $\sim 1$ msec. The beam voltage is 84 kV. The maximum efficiency is 30% at 1MW oscillation, and 1.56 MW oscillation was obtained at the beam current of 69 A. The allowable misalignment between the gyrotron axis and SCM axis is only 0.1 mm which is one order smaller than that of $TE_{31,8}$ oscillation. However, it can be concluded that the stable single mode oscillation is possible at higher order mode $TE_{31,12}$, which indicates a possibility of the 1.5MW level long pulse operation. In addition, the 50 % operation may be possible with the application of the depressed collector.
4. Summary

The recent research and development of 170GHz gyrotron were presented. For the development of ITER gyrotron, the gyrotron and the test facility were modified for CW operation. The pre-programming control of heater power was introduced to obtain the constant current to avoid the power decrease during the shot. The quasi-optical mode converter system was improved to reduce the stray radiation. In the preliminary experiment, the results of 0.2 MW/480 sec and 0.13 MW/600 sec were obtained. However, the power profile of the output RF beam was different from the designed circular beam. The pulse extension experiment at higher power will be re-started after the replacement of the mirrors in the MOU to obtain good coupling of the power with the HE_{11} mode of the corrugated waveguide, which leads to the 1 MW/CW dummy load. In parallel, the study of the high order mode oscillation was carried out using a short pulse gyrotron. The operation mode is TE_{31,12} which allows the 1.5MW level CW operation. In the ~1 msec experiment, stable oscillation at TE_{31,12} mode was confirmed up to the power of 1.56 MW. The maximum efficiency was 30% at 1 MW output. The result indicates that the stable oscillation over 1 MW at 170 GHz is possible using the simple cylindrical cavity.

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