Performance of 170 GHz high-power gyrotron for CW operation

A.Kasugai, K.Sakamoto, R.Minami, K.Takahashi, N.Kobayashi, and T.Imai 1)

Naka Fusion Research Establishment, Japan Atomic Energy Research Institute (JAERI),
801-1 Mukoyama, Naka-machi, Ibaraki 311-0193, Japan

e-mailcontact of main author: kasugai@naka.jaeri.go.jp

Abstract. A quasi-steady-state oscillation of 100 s with 0.5 MW power level was demonstrated on a 170 GHz ITER gyrotron. The temperature of major components of the gyrotron reached the steady state, which gives a prospect for a 1 MW-CW, 170 GHz ITER gyrotron. For a further pulse extension and power increase, the gyrotron and its control system have been modified; i.e. a built-in radiator has been optimized for improvement of an efficiency of gyrotron output power and reduction of stray radiation, and pre-program controls of a cathode heater power, magnetic field at the cavity and voltage between anode and cathode, have been employed for stabilization of the beam current and the output power.

1. Introduction

The ITER requires a 170 GHz high-power gyrotron system with a total source power of 24 MW, for electron cyclotron heating (ECH), current drive (ECCD) and suppression of plasma instabilities [1]. The intensive development of a 170 GHz gyrotron with 1 MW, continuous wave (CW) operation and 50% efficiency has been carried out to satisfy the requirements of the ITER. Integration of breakthrough technologies was achieved by JAERI; i.e. 1 MW oscillation at high order mode cavity [2], energy recovery by a depressed collector [3], and a synthetic diamond window [4]. At the last IAEA fusion energy conference, high power operation of 1.3 MW (1 ms), 0.9 MW-9 s operation, long pulse operations of 133 s (0.2 MW), high efficiency operation of 50% were reported [5, 6]. However, the extension of the pulse duration with high power was limited by a sudden pressure increase inside the gyrotron.

This paper describes major recent achievements of the ITER gyrotron development in JAERI, i.e. the quasi steady state oscillation and the prospect toward stable 1 MW-CW operation. In addition, the paper also describes improvement strategies for reliable operation toward stable 1MW-CW output; i.e. that is modification of built-in radiator for higher output efficiency and reduction of the diffraction loss, and that is pre-programming control of a cathode heater power, magnetic field at the cavity and voltage between anode and cathode for stabilization of beam current and output power.

2. Structure and design of the gyrotron

A photograph of 170 GHz gyrotron and a cut-away view of the gyrotron are shown in Fig. 1 and Fig. 2, respectively. The magnetron injection gun (MIG) with triode type makes a hollow beam of the gyrating electrons with an energy of ~80 keV, which is injected into an

1) present address: Plasma Research Center, University of Tsukuba,
1-1-1 Tennodai, Tsukuba-shi, Ibaraki 305-8577, Japan

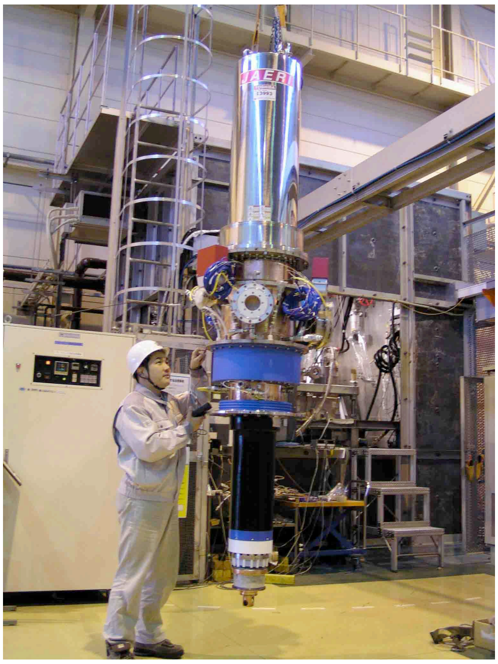

Fig.1: Photograph of 170GHz gyrotron. Height is ~3m and weight is ~800kg.

open-ended cylindrical cavity. A $TE_{31,8}$ mode RF wave is generated in the cavity by principle of electron cyclotron resonance maser. The $TE_{31,8}$ mode is converted into a Gaussian profile beam by a built-in radiator and mirrors, and output through a diamond window with 80 mm aperture with low loss tangent of 2 x 10^{-5}. By the edge cooling with water, the center temperature of the diamond disk stabilizes at ΔT=45 °C in the calculation with 1 MW-CW output. The gyrotron operation has been carried out on a RF test stand (RFTS) in JAERI. The capability of RFTS is 90kV/50A for CW operation, and 90kV/80A up to a few milliseconds. A power supply is composed of main power supply (MPS) and beam acceleration power supply (APS, 100kV/300mA with high voltage stability of ±0.5%). The voltage difference between MPS and APS appears as a retarding potential on the spent electron beam at a ceramic insulator (DC break made of silicon nitride) for a depressed collector operation (CPD). A high-speed switching of the MPS is done by IGBT (Insulated Gate Bipolar Transistor) with voltage rise and shutdown time of ~6μs [7]. The electron beam is guided to the cavity along a compressed magnetic field up to ~6.7 T, which is generated by a superconducting magnet (SCM) built-in 4K-refrigiator. The output power from the gyrotron is focused to the corrugated waveguide of 31.75 mm in diameter using two phase-correction mirrors in the matching optics unit (MOU). The MOU and transmission line are evacuated to avoid the arcing in the RF transmission. The transmitted power as a HE_{11} mode is absorbed by a long pulse 1.2 MW dummy load placed after ~12 m corrugated waveguide via two miter bends.

The heating of the inner components is caused by a power deposition of the stray radiation due to diffraction loss corresponding to the mode conversion loss from $TE_{31,8}$ to Gaussian beam in the long pulse operation. Diffraction loss is 6.2% of the oscillation power at the cavity in the calculation. Though most of the power escapes through the insulators (DC break and sub-window) to outside of the gyrotron, a small amount of the power is absorbed as ohmic loss on the inner surface of the gyrotron.

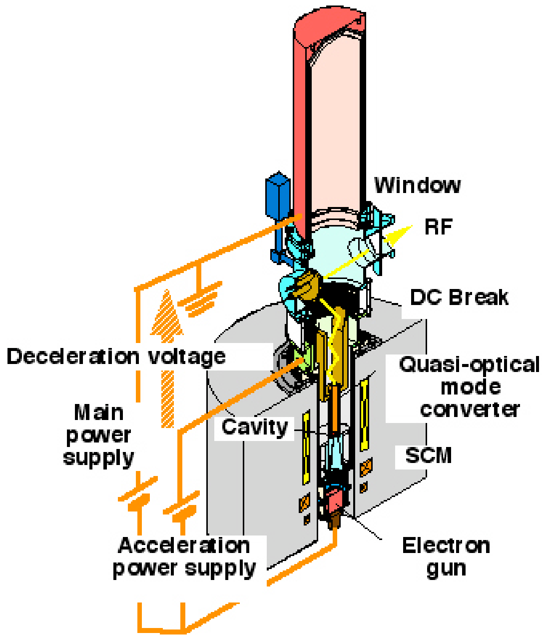

Fig.2: Cut-away view of the gyrotron.

3. Quasi-steady state operation by reduction of local stray power deposition

The measured stray radiation power was estimated to be about 9% of the total oscillation power. A part of the stray power deposits to the bellows section attached to the steering mirror for adjusting the RF beam direction to the output window. After intensive measurement of temperature of the gyrotron components, it was comfirmed that this stainless steel bellows was the source of the outgassing. The temperature on the bellows surface measured by a thermo-coupler linearly increases with the pulse length as shown in Fig. 3. This result indicates that the temperature exceeded the baking temperature (450 °C) after about 15 s at 0.8 MW output.

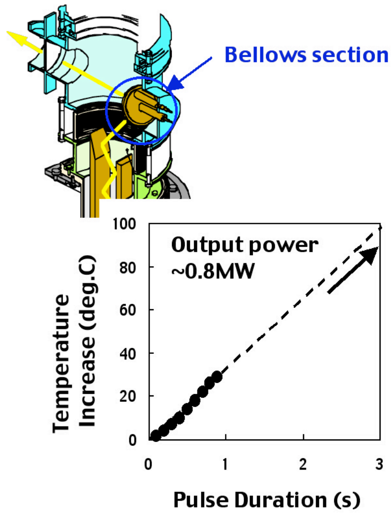

Fig.3. Temperature increase of the bellows section.

The countermeasures for local power deposition on the bellows are as follows,

(1) Reduction of the ohmic loss by RF shield and Cu coating of ~11 μm on the bellows.

(2) Enhancement of water cooling capability.

The structures of the RF steering mirrors before and after modification are shown in Fig. 4. By the Cu coating on the bellows, the heating rate of the bellows was reduced to less than 1/10 of the original one, and the time constant of thermal diffusion without cooling condition was reduced from 270s to 90 s by cooling of bellows in addition to Cu coating. As a result, the sudden pressure increase was suppressed in the long pulse operation. Consequently, 0.5 MW power level operation for 100 s was demonstrated without significant conditioning.

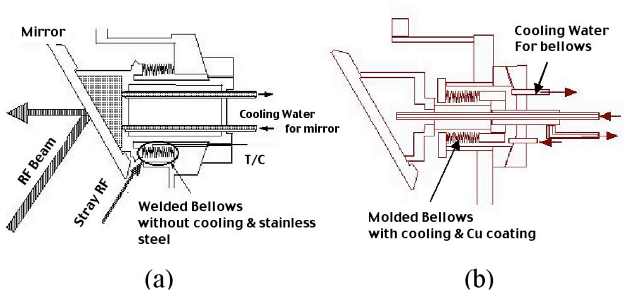

Fig.4: RF steering mirror (a) before and (b) after modification.

The temperature of the major components reached the steady state within the 100 s operation. Figure 5 shows a typical time evolution of the temperatures at the collector surface, fluorinate liquid for DC break cooling and the center of the output diamond window cooled by fluorinate liquid at the edge for the 100 s operation with 0.5 MW level output power. The collector temperature was 120 °C in steady state. The DC break for depressed collector operation, whose temperature increases

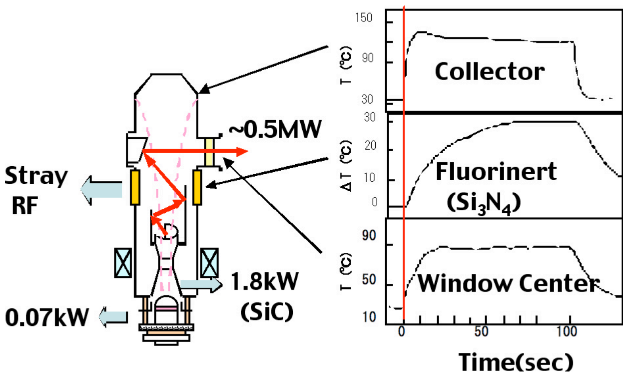

Fig. 5.: Typical time evolution of the temperature changes of major components in the gyrotron for a 100 s operation with 0.5MW level output power.

due to the absorption of the stray radiation, is cooled by the fluorinate liquid for high voltage isolation. The temperature of the fluorinate liquid was acceptable value, ΔT~30 °C. Temperature increase of the center of the disk measured by an IR camera was ΔT ~60 °C, and it is possible to transmit the 1 MW power by the enhancement of the flow velocity. These results give the prospect of the 1 MW-CW operation in the thermal viewpoint.

In this gyrotron, SiC cylinders are installed in the beam tunnel in order to suppress the parasitic oscillation [8]. By this effect, absorbed power by the SiC cylinder was reduced 1.8kW, and that escaped to the electron gun was less than 70W in the case of ~530 kW output power.

4. Prospect for 1MW-CW operation

It was clarified in the process of pulse extension that the present 170GHz gyrotron has two major issues for reliable and stable 1MW-CW operation. One is amount of diffraction loss and heat deposition in the radiator. The other is a decrease of output power with pulse duration. To solve these issues, following modifications have been carried out for the next 170 GHz gyrotron.

(1) Improvement of the radiator

On the radiator used in the present gyrotron, ~3% of the radiated power cannot enter into the first mirror in the calculation and total diffraction loss at the mode converter is about 6% in the calculation as shown in Fig. 6. In the present gyrotron, the adiabatic radiator (single helix) without taper was employed. For this reason, spilt power over the first mirror is relatively large and parasitic oscillation becomes significant in the entrance of the radiator, when the oscillation efficiency is low.

To reduce the diffraction loss, inner surface of the radiator was optimized with CCR-LOT code [9] for the next gyrotron. The deformation of the radiator, field intensity on the inner wall and the field intensity on a screen placed 60mm from the radiator axis are shown in Fig.7 (a), (b) and (c), respectively. The radiator has a taper of 0.2degree and the output radius is 21.5mm. It is designed that 99.5% of the radiated power from radiator enter on the first mirror in the calculation. Since suppression of the stray radiation is key issue, improvement of quasi-optical mode converter aiming increase in mode conversion efficiency more than 97% is in progress.

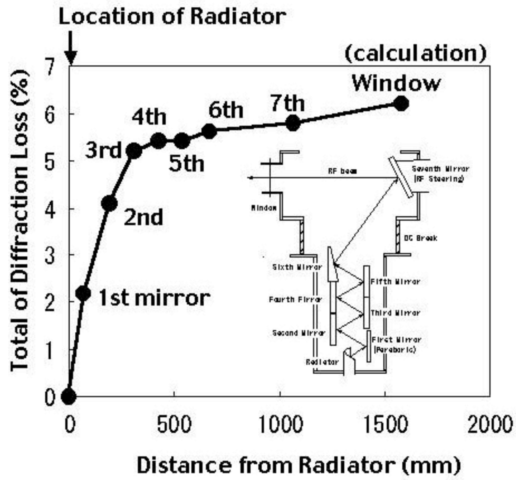

Fig.6: Diffraction loss of the mode converter in the present gyrotron.

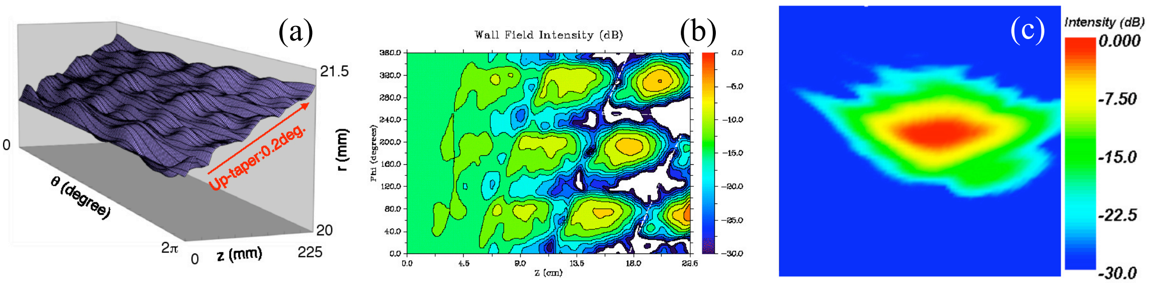

Fig.7: Design of improved radiator for the next gyrotron, (a) deformation of the inner wall, (b) field intensity on the radiator wall, (c) field intensity on the screen placed 60 mm from the radiator axis, 150 mm x 150 mm.

(2) Pre-programming control of beam current, magnetic field and cathode-anode voltage

As shown in Fig.8 (a), beam current decreased as pulse duration expanded from 35A to 25A during 0.5MW/100s operation. Beam voltage was 71.5kV. Consequently, the power decreased from ~0.6 MW (at short pulse) to ~0.46 MW (average power during 100 s) as the current decreased. The current decrease is mainly caused by cathode cooling due to electron emission [10]. One method to compensate the current decrease is to boost the heater power of the electron gun. The Fig.8 (b) shows a transition of the beam current when the heater power was enhanced from initial value 190W at t=0 s. Here, the electron beam was emitted every 6 s with the pulse duration of 0.1 s. At 250W, the current increase is 0.09 A/s, which is enough to compensate the current drop.

To sustain stable oscillation with the target mode $TE_{31,8}$ against change of the beam current, it is necessary to control the magnetic field at the cavity (B_c) with the pulse duration. For example, when the beam current decreases less than oscillation starting current, change of the oscillation mode from $TE_{31,8}$ to $TE_{30,8}$, so called mode jump, occurs . For suppression of the mode jump, it is important to control of oscillation condition by increasing of B_c at the cavity.

In addition, it was found that power decrease was also caused by decrease in electron velocity ratio ($\alpha = v_\perp/v_{//}$) for long pulse operation, which is caused by reduction of the space charge of the electron beam due to the ion trapping [11]. For this reason, output power for long pulse duration such as more than 1 s decreased by about 10% in comparison with the power in short pulse operation as shown in Fig. 9. At low beam current, the power for long pulse is equal to the power for short pulse. However, the difference of each power expanded gradually with the beam current. For example, at the beam current of 50 A, the power decreased from 0.9

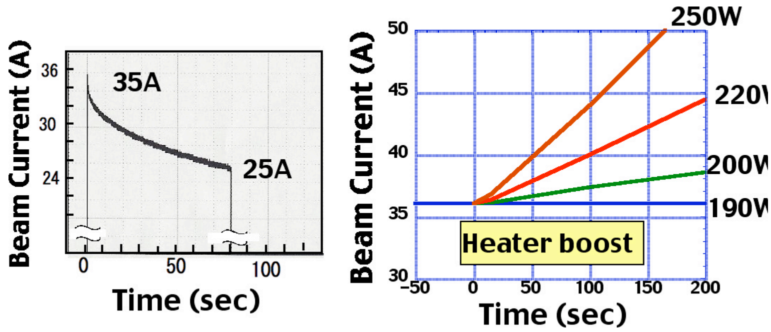

Fig.8: (a) Current decrease in the shot.
(b) Current increase by heater boost.

MW for short pulse to 0.8MW for long pulse. The different parameter between short pulse operation without CPD and long pulse operation with CPD is only optimized magnetic field at the cavity. Optimized B_c at cavity up-sifted from 6.63 T at short pulse to 6.69 T at long pulse. This phenomenon is caused by increase in effective beam voltage at the cavity due to relaxation of space charge effect of electron beam. Hence, it is expected that the output power will be sustained by holding the electron velocity ratio α due to control of the voltage between the cathode and anode of the triode gun using pre-programming for long pulse operation.

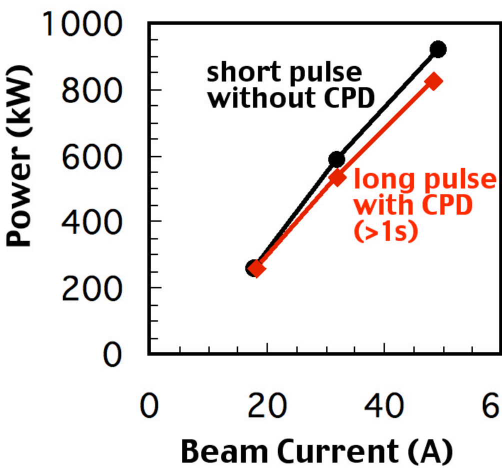

Fig.9: Power decrease in long pulse operation due to α decreasing.

5. Summary

The recent progress of gyrotron development in JAERI is presented. The development of high-power 170 GHz gyrotron has attained quasi-steady-state oscillation of 100 s with 0.5 MW power level for ITER. The temperature of major components of the gyrotron stabilized, which indicates a prospect for a 1 MW-CW, 170 GHz ITER gyrotron. For stable 1 MW-CW operation, the improvement of built-in radiator for suppression of stray radiation and heat deposition in the radiator, and pre-programming controls of the cathode heater power, magnetic field and voltage between cathode and anode are under way for the next 170 GHz gyrotron. These modifications will contribute to the stabilization of the beam current and the output power for CW operation.

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