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R. Minami, T. Kariya, T. Imai, T. Numakura, Y. Endo, H. Nakabayashi,
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R. Minami[1], T. Kariya[1], T. Imai[1], T. Numakura[1], Y. Endo[1], H. Nakabayashi[1], T. Eguchi[1], T. Shimozuma[2], S. Kubo[2], Y. Yoshimura[2], H. Igami[2], H. Takahashi[2], T. Mutoh[2], S. Ito[2], H. Idei[3], H. Zushi[3], Y. Yamaguchi[4], K. Sakamoto[5], Y. Mitsunaka[6] and GAMMA 10 Group[1]

[1]Plasma Research Center, University of Tsukuba, Ibaraki, Japan
[2]National Institute for Fusion Science (NIFS), Gifu, Japan
[3]Research Institute for Applied Mechanics, Kyushu University, Fukuoka, Japan
[4]Research Center for Development of Far Infrared Region, University of Fukui (FIR FU), Fukui, Japan
[5]Japan Atomic Energy Agency (JAEA), Ibaraki, Japan
[6]Toshiba Electron Tubes and Devices Co., Ltd (TETD), Tochigi, Japan

E-mail contact of main author: minami@prc.tsukuba.ac.jp

Abstract. Over-1 MW power gyrotrons for electron cyclotron heating (ECH) have been developed in the joint program of NIFS and University of Tsukuba. The obtained maximum outputs are 1.9 MW for 0.1 s on the 77 GHz Large Helical Device (LHD) tube and 1.0 MW for 1 ms on the 28 GHz GAMMA 10 one, which are new records in these frequency ranges. In long pulse operation, 300 kW for 40 min at 77 GHz and 540 kW for 2 s at 28 GHz were achieved. A new program of 154 GHz 1 MW development has started for high density plasma heating in LHD and the first tube has been fabricated. These lower frequency tubes like 77 GHz or 28 GHz one are also important for advanced magnetic fusion devices, which use Electron Bernstein Wave (EBW) heating / current drive. As a next activity of 28 GHz gyrotron, we have already started the development of over-1.5 MW gyrotron and a new design study of 28 GHz / 35 GHz dual frequency gyrotron, which indicates the practicability of the multi-purpose gyrotron.

1. Introduction

High power gyrotrons operated in the millimeter wave range are used successfully in experiments on ECH of the plasma in tokamaks and stellarators [1,2]. The main efforts have been aimed at increasing the energy of the output radiation of gyrotrons in this range, for example, International Thermonuclear Experimental Reactor (ITER) frequency of 170 GHz, 1 MW, continuous wave (CW) operation [3,4,5]. In addition, it is interesting that ECH is capable to heat super dense core (SDC) plasma more than 10^{21} m^{-3}, if we could increase frequency, as density limit is proportional to square of frequency. It may be required 300 GHz ECH, whose gyrotron development could not be impossible after the success in diamond window. If EBW is employed, it is more accessible to the center of the SDC plasma with lower frequency. These ECH features would make the role of ECH far more important in future.

In GAMMA 10, which is a tandem mirror device in Plasma Research Center (PRC) of University of Tsukuba, it is essential to achieve high confining potential with ECH. From power scaling of confining potential in GAMMA 10, higher the ECH power is, stronger the formation. The GAMMA 10, therefore, has started the ECH upgrade program [6], in collaboration with JAEA and TETD who are developing the ITER 170 GHz tube and the new record of ion confining potential was achieved. Based on these, a MW tube project has been started to develop 28 GHz 1 MW for GAMMA 10. It has also found that ECH has capability to control radial electric field profile, which is comprehensively important for magnetic confinement systems. The ECH upgrade is also essential for LHD in NIFS to achieve the efficient transport control, high T_e plasma and high performance CW operation [7].

Based on these, a MW gyrotron project has been started as the joint program with NIFS to develop over-1 MW tube of 77 GHz CW for LHD and 28 GHz 1 MW for GAMMA 10 by all Japan efforts collaborating with JAEA and TETD. These frequency ranges are also important for advanced magnetic fusion devices like spherical tokamaks, who use EBW heating / current drive, and other low magnetic field devices. In low frequency gyrotrons, a control of diffraction loss is a key to open a CW operation with MW level or even multi-MW power. Here our challenge to reduce it are presented and the present status of the outcomes of this challenge. Based on above successful results, a new program of 154 GHz 1 MW development has started for high density plasma heating in LHD.

2. Development of 77 GHz and 154 GHz gyrotrons for LHD

As the NIFS-Tsukuba joint program, 77 GHz 1 MW gyrotron for LHD has been started since 2006 [8]. In low frequency gyrotrons, a control of the diffraction loss is a key to open a CW operation with MW level or even multi-MW power.

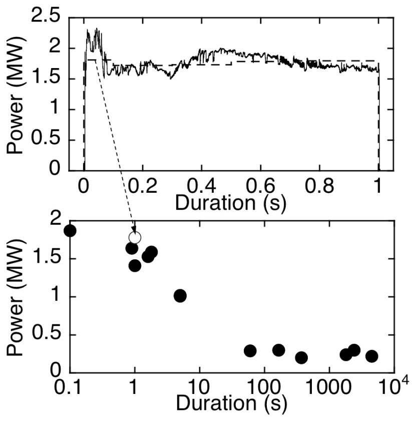

Fig. 1. Achievements of the stable operation in the 77 GHz gyrotron development.

For more than 1.5 MW output, the Magnetron Injection Gun (MIG) and the cavity have been redesigned to suppress the effective pitch factor α ($= v_{\perp}/v_{//}$) decline in high beam current. Besides, an internal mode converter and mirrors are carefully optimized to minimize the electric field at the window edge and the diffraction loss. The design parameters of the most recent 77 GHz tube are 1.5 MW for 2 s and 0.3 MW for CW. The achievement of the development through three tubes is shown in Fig. 1. The obtained maximum output is 1.9 MW at the Matching Optics Unit (MOU) outlet and the efficiency experimentally obtained is 38% with depressed collector operation (CPD). Their operation could be highly optimized by means of two-step rise of the anode voltage, which extends the operation parameters. In the first step, in which the voltage is sufficiently lower than the optimized value, a beam current flows with no RF oscillation. Then in the second step, the voltage is increased to the optimized value to generate RF power. We can operate with the optimized anode voltage by avoiding the lower collector voltage period. This procedure has a twofold gain. Being selected a time duration of the first step appropriately (~100 ms), a so-called ion neutralization of the DC space charge fields of the electron beam can occur in the cavity during the period of the first step. At the beginning of the second step, the electron beam can be accelerated by a full body voltage. The other parameters (anode voltage, magnetic field, etc.) can be highly optimized toward the designed values [9]. The 1.9 MW in sub-second operation is a world record and the strong step to multi-MW gyrotrons. Three 77 GHz gyrotrons have already been installed and operated stably in LHD. More than 3.4 MW has been injected into LHD plasma contributing to producing the electron temperature T_e of 20 keV [10].

Based on above successful results, a new program of 154 GHz 1MW gyrotron has been started for second harmonic heating in LHD. The major issues of the tube are the heat due to ohmic and dielectric losses, cavity loss and diffraction loss. $TE_{28,8}$ cavity, synthetic diamond window and depressed collector are employed as in the 77 GHz one, against these kind of problems except the diffraction [11,12]. Figure 2 shows the simulation result of beam current (I_k) dependence of output power (P_0) and efficiency (η) without CPD in case of the pitch factor α = 1.1 and the acceleration voltage V_{bk} = 80 kV. The output power increased with the beam current without saturation, and over 1 MW was obtained at I_k = 50 A. It is expected that overall total efficiency is improved up to about 50% (original efficiency is about 35%) by using CPD. In the new design of the internal mode converter and mirrors, which is essential to reduce the diffraction loss, it is expected that the total power coupled to the waveguide mode is 97.1%. This coupling efficiency is nearly equal to the maximum value which has been obtained in MW long pulse tubes. The first 154 GHz tube fabrication has been just completed taking these advanced designs of over 1 MW output.

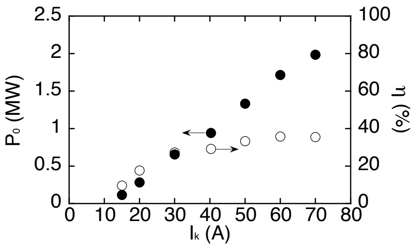

Fig. 2. Simulation result of beam current dependence of output power (closed circles) and efficiency (open circles) in 154 GHz gyrotron design.

The first short pulse test of 154 GHz gyrotron was performed at PRC test stand. The maximum power of 1.06 MW was obtained at the MOU outlet, with the beam voltage of 80 kV and the beam current of 48.5 A. And the maximum output efficiency of 28.6 % without CPD was obtained with 0.96 MW. The experimentally measured burn patterns of RF beam at the output window and the MOU showed the Gaussian-like profiles agreed well with the designed result. The output RF frequency was confirmed to be 154.10 GHz. From these experimental results, the $TE_{28,8}$ mode oscillation in the cavity was confirmed. Beam current (I_k) dependences of output power (P_0) and output efficiency (η) are shown in Fig. 3. The P_0 is measured calorimetrically by the SiC water load at the output window. The P_0 increases with increasing I_k without saturation. The experimentally measured transmission efficiency of the MOU is about 100 % within the measurement errors. The RF transmission loss in the gyrotron is estimated over 2.4 % by calorimetrically measured results of stray RF leaking from the sub-window and the DC break ceramics [13].

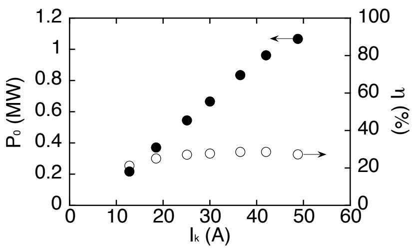

Fig. 3. Experimental results of beam current dependences of output power (closed circles) and output efficiency (open circles) with the beam voltage of 80 kV at the output window.

Next, the gyrotron was installed and tested in NIFS for the LHD experiment. In the performance test of NIFS, similar test results obtained at the PRC test were confirmed. The maximum total efficiency with CPD enhancement was 38.1 % with the output power of 660 kW, the CPD voltage of 25 kV and the beam current of 31.2 A. Higher power and long pulse operation at LHD are in progress.

3. Development program of 28 GHz gyrotron

28 GHz gyrotrons are required in recent plasma experimental devices. For example, a 0.4 MW CW gyrotron is needed for the ECH system of QUEST in Kyushu University, furthermore, a 1.5 - 2.0 MW several seconds gyrotron is needed for the ECH system of GAMMA10 (GAMMA 10/PDX project) and NSTX of PPPL [14].

The 1 MW, a few seconds, 28 GHz gyrotron development for GAMMA 10 and other low B field device ECH source has been started, based on experiences of both 28 GHz 500 kW and 77 GHz 1 MW tubes. The MIG design of the 1 MW tube employs the triode gun to have flexibility of α control by anode voltage. The expected pitch factor α is 1.1 - 1.2 with α spread of 6 - 7% at the beam voltage of 80 kV and the anode voltage 37 - 39 kV. The height is 2.4 m and the weight is about 700 kg. The cavity mode has been chosen as $TE_{8,3}$, from the consideration of beam current density, which is ~3 A/cm^2 at 40 A. The design of the inner mode converter is one of the key design point of the 28 GHz gyrotron, since the reduction of the stray RF in low frequency gyrotrons is far more important than other higher frequency tubes. The diameter of the body section is enlarged as far as possible within the restriction of the SCM bore to have the larger mode convertor and mirrors for the reduction of the diffraction loss and is, therefore, larger compared with the 77 GHz and ITER tubes. As the result, the mode conversion efficiency of ~95% has been obtained even at 28 GHz.

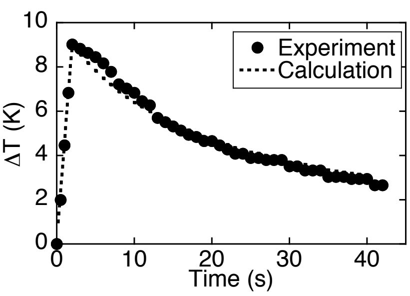

Fig. 4. Time dependence of temperature increase in 450 kW 2 s shot.

The obtained maximum output is 1.0 MW at 40 A [15]. In long pulse operation, the new record operation of 540 kW for 2 s has been obtained. Figure 4 shows the time dependence of temperature increase (ΔT) at the center of the window in 450 kW 2 s shot. Experimental data (closed circles) are measured by an infrared camera, which is calibrated by the thermo couple. From this result, the dielectric loss (tanδ) of the sapphire window is estimated to be 3.3×10^{-5} at 28 GHz. The temperature increase is not so much (about 9 K). It decreases after the RF pulse, and the window temperature recovers to the initial level within 2.4 min. It is expected that 1 MW 5 s oscillation (the estimated ΔT is 50 K) is achieved with sufficient shot interval, for example, over 3.7 min. Upgrade of the dummy load and the power supply is in progress, and higher power test will be started.

Based on these results, the improved design study for CW operation, which is required in QUEST of Kyushu University, was carried out. Figure 5(a) shows the simulation results of RF pulse width dependences of window temperature in cases of output power of 0.4 MW and

1 MW, calculated with the tanδ considering the experimental result in Fig. 4. Figure 5(b) shows that in cases of heat transfer rate h = 0.3 and 0.03 with output power 0.4 MW in a double disk window. As shown in Fig. 5(a), the operation of 1.5 MW 2 s is possible by the single disk sapphire window, but the operation of 0.4 MW CW isn't possible. While the operation of 0.4 MW CW is possible by a double disk sapphire window with the heat transfer rate h > 0.03 $\mathrm{W/cm^2 \cdot K}$ from Fig. 5(b). By the adoption of the surface cooled double disk sapphire window, peak of ΔT is expected to be less than 40 K for 0.4 MW CW operation, which is required in QUEST. Besides, the MIG and the cavity have been designed to suppress the effective pitch factor α decline by the better laminarity of electron beam in high beam current, thus it is expected that more than 1.5 MW for a few seconds operation can be achieved. The $TE_{8,3}$ mode RF wave is converted to the Gaussian-like beam by the built-in quasi-optical mode converter, and the RF beam is transmitted by four pieces of mirror system to the outside of the tube through the output window. The output RF beam is adjusted its profile and phase by the MOU, and couples to the corrugated waveguide as HE_{11} mode. The total transmission efficiency from the mode converter to the output window is 94.7% and to the corrugated waveguide is 90.2% in the first tube. The improved designs that reduce the side lobe of RF beam launched from the launcher and increase the transmission efficiency of the mirrors is being performed now with the target of total transmission efficiency over 95%. The calculated result of the electric field intensity near the first mirror of mode converter on a cylindrical surface surrounding the launcher is shown in Fig. 6. Calculated total output efficiency at the window is improved from 94.7% to 98.5%.

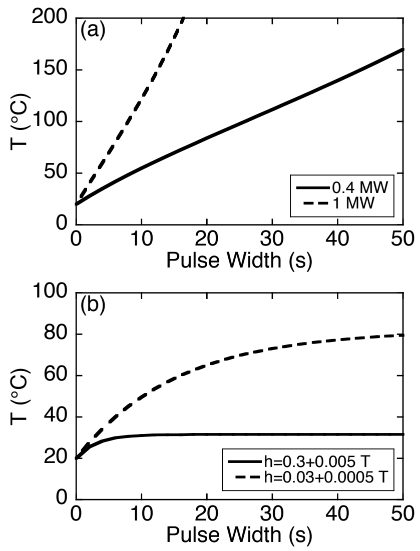

Fig. 5. Simulation result of RF pulse width dependences of window temperature. (a) output power of 0.4 MW (solid curves) and 1 MW (dashed curves) cases in the single disk window. (b) heat transfer rate h=0.3 (solid curves) and h=0.03 (dashed curves) cases with output power 0.4 MW in a double disk window.

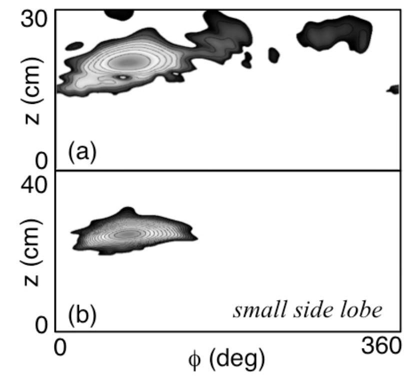

Fig. 6. Radiated field patterns near the first mirror surface of (a) first tube and (b) new design.

4. Activities of 28 GHz gyrotrons

After successful results of 28 GHz Mega-Watt tube, we put the emphasis on the development of a multi-purpose gyrotron, which has the performance of more than 1.5 MW a few seconds operation in 28 GHz which is required in GAMMA 10 high heat flux experiment and NSTX of PPPL, 0.4 MW CW operation for QUEST of Kyushu University and 1 MW level in 35 GHz range operation for Heliotron J of Kyoto University.

The new program to simulate the divertor plasma which utilizes mirror advantages have been started, in addition to core confinement studies as the mainframe 6 year work plan [16]. Since the boundary plasma physics is the key to sustain the steady-state fusion reactor plasma, the divertor plasma control and plasma wall interaction are urgent issues for ITER and the fusion research. Making use of resources of GAMMA 10 device, we started the GAMMA 10/PDX project, where PDX denotes **P**otential control and **D**ivertor simulating e**X**periment. The divertor plasma simulator which makes use of high heat flux generated at the open end of the GAMMA 10 is called E-Divertor. It is relevant to the fusion reactor peripheral plasma. This is one of the uniqueness of the GAMMA 10 E-Divertor. The development of the high power 28 GHz gyrotron is major hardware efforts in GAMMA 10/PDX project. By modulating the ECH power, we can obtain arbitrary pulse heat load patterns. By changing the on/off timing, we can simulate the ELM intermittent heat pulses. One pulse heat load energy density increases almost linearly with ECH power. The maximum energy density obtained is 0.05 MJ/m^2 with about 380 kW 5 ms pulse. This is still far lower than that of ITER ELM (0.5 - 1 MJ/m^2). We can expect the ITER level energy density by upgrading ECH to MW level [14,17]. We have already started development of over-1.5 MW gyrotron and the new MIG is now being installed in the present gyrotron as described in Sec. 3. Figure 7 shows the simulation result of beam current (I_k) dependence of output power (P_0) at the cavity without CPD in cases of pitch factor α = 1.3, 1.2 and 1.1, and the acceleration voltage V_{bk} = 80 kV. The output power increased with the beam current without saturation, and over 1.5 MW was obtained at I_k > 50 A, which suggest practicability of the ~2 MW power gyrotron output.

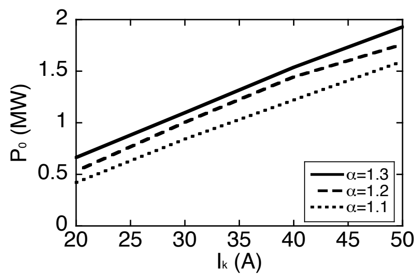

Fig. 7. Simulation result of beam current dependence of output power at the cavity in cases of pitch factor α = 1.3 (solid curves), α =1.2 (dashed curves) and α =1.1 (dotted curves).

For the ECH system of QUEST in Kyushu University, a 0.4 MW CW gyrotron is needed, as described before. It is started to apply the first Tsukuba 28 GHz tube described in Sec. 3 to the preliminary ECH/ECCD experiment in QUEST, based on the NIFS bilateral collaboration. The operation region of the gyrotron is limited under the acceleration voltage V_{bk} = 70 kV and the beam current I_k = 25 A due to the specification of the power supply. For the first tube, 450 kW a few seconds was already achieved with the required operation region in PRC test stand. Transmission lines and the power supply required for the Tsukuba 28 GHz tube installation have been prepared. In parallel, the development of the 0.4 MW CW gyrotron for QUEST CW program has been started, as the new design study for 0.4 MW CW gyrotron is described in Sec. 3 [18].

Application of the Tsukuba gyrotron to Heliotron J in Kyoto University program has also been started. 1 MW level in 35 GHz gyrotron is required for Heliotron J. If 35 GHz oscillation is possible in the 28 GHz gyrotron, it would be quite efficient for tri-lateral research collaboration. So we have started a new design study of 28 GHz / 35 GHz dual frequency gyrotron. As for the 35 GHz design, using the same cavity as 28 GHz one, oscillation at 35 GHz range is optimized and the mode of $TE_{9,4}$ has been chosen. It is found that more than 800 kW output is expected with 50 A beam current. The transmission efficiency at 35.45 GHz from the launcher to the first parabolic mirror using the optimized launcher for multi-frequencies is 92.4%, while that at 28 GHz is 97.8%. The total efficiency from the mode converter to the output window is not so high because the mirrors of the mode converter have not been optimized sufficiently yet. As for the sapphire window, a double disc window is necessary for CW and the thickness of the disc must be 2 times thicker than present one to reduce the reflection for 35 GHz range transmission [19].

5. Conclusion

The ECH system is supreme heating scheme for magnetic fusion device, only which can access to the high density and high temperature reactor plasma without major technical and physical difficulties. The development of gyrotron is indispensable for this goal. For the upgrade of GAMMA 10 and LHD performances, the joint program of NIFS and University of Tsukuba to develop over-1 MW gyrotrons have been carried out in collaboration with JAEA and TETD. The obtained maximum outputs are 1.9 MW for 0.1 s on the 77 GHz LHD tube and 1.0 MW for 1 ms on the 28 GHz GAMMA 10 one, which are new records in these frequency ranges. In long pulse operation, 300 kW for 40 min at 77 GHz and 540 kW for 2 s at 28 GHz were achieved. Three 77 GHz gyrotrons have already been installed and operated stably in LHD. More than 3.4 MW has been injected into LHD plasma contributing to producing the electron temperature T_e of 20 keV. The design study of new 154 GHz 1MW gyrotron for LHD device has been performed. In the first short pulse test, over 1 MW output was confirmed and profiles of RF beam were agreed with design results. The pitch factor α decreased with increasing the beam current. It can be considered that the α spread is bigger than the calculation result of MIG code. The production of MIG with high α and low α spread at high beam current is one of keys for the high power and high efficiency gyrotron development. The long pulse test of 154 GHz 1 MW gyrotron is in progress. In the 28 GHz 1 MW gyrotron development, the output power was achieved 1 MW in the short pulse test. The pulse duration was extended to 2 s with 0.54 MW in the long pulse test. The temperature increase of the sapphire single disk window was 9 K with 0.45 MW for 2 s. On the basis of the long pulse test, the improved design of 28 GHz gyrotron carried out to aim the higher power and CW operation. It is found that the operation of more than 1.5 MW several seconds is possible by the single disk sapphire window. Using a double disk window, the operation of 0.4 MW CW is enabled. The cathode angle has been made deeper to obtain the better laminar flow of electron beam in front of the cathode. This improvement of electron beam parameters will lead to the higher oscillation efficiency and more stable operation. The mode converter design is improved to reduce RF diffraction loss. As a calculation result, the transmission efficiency from the mode converter to the window is improved from 94.7 % to 98.5 %. It is expected that the operations of 0.4 MW CW and more than 1.5 MW in a few seconds can be achieved.

Acknowledgements

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