Development of Over-1 MW Gyrotrons for the LHD and the GAMMA 10 ECH Systems

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Abstract. For the ECH upgrade program of LHD and GAMMA10, over-1 MW power gyrotrons have been developed in the joint program of NIFS and University of Tsukuba. The gyrotrons for LHD and GAMMA 10 have $TE_{18,6}$ cavity and a diamond window at 77 GHz, and with $TE_{8,3}$ cavity at 28 GHz, respectively. The maximum outputs obtained are 1.9 MW for 0.1 s on the 77 GHz LHD tube and ~ 1 MW on the 28 GHz one, which are the new records in these frequency ranges. The results of 1.8 MW for 1 s, 1.6 MW for 1.8s, 1 MW for 5 s, 300 kW for 40 min and 200 kW for 75 min were achieved at 77 GHz. In the long pulse operation, it is found that the stray RF is the major cause limiting the pulse length. Design improvements of the diffraction loss, the cavity and pitch factor α ($= v_\perp / v_{/\!/}$) dispersion of the MIG have made the 77 GHz tube performance better, which have enabled to demonstrate 1.9 MW output and long pulse operation for more than 1 hour with 200 kW. The three 77 GHz gyrotrons have already been installed in the LHD ECH system and more than 3 MW has been injected into LHD plasma. In the 28 GHz long pulse operation, 400 kW for 1 sec has been obtained and it is found the higher and longer pulse operation would be possible with the operation optimization and conditioning.

1. Introduction

Among the heating systems, an ECH has many advantages in both physics and technology on the application to the magnetic confinement fusion devices. It has many reliable functions of the plasma heating, current drive, plasma control and so forth and hence has been employed as one of the major heating schemes of ITER [1]. In addition, it is interesting that ECH is capable to heat super dense core (SDC) plasma [2] more than $10^{21}m^{-3}$, if we could increase the frequency, as the density limit is proportional to the square of the frequency. It may be required 300 GHz ECH, whose gyrotron development could not be impossible after the success in diamond window [3]. If EBW is employed, it is more accessible to the centre of the SDC plasma with lower frequency [4]. These ECH features would make the role of the ECH far more important in future. It is also essential for the tandem mirror devices to achieve high confining potential with the ECH. From power scaling of confining potential in GAMMA 10, the higher the ECH power is, the stronger the potential formation. The GAMMA 10, therefore, has started the ECH upgrade program [5], in collaboration with Japan Atomic Energy Agency (JAEA) who is developing the ITER 170 GHz tube [6] and new record of the ion confining potential was achieved. It has also found that the ECH has capability to control radial electric field profile [7], which is comprehensively important for magnetic confinement systems. The ECH upgrade is also essential for LHD in National Institute for Fusion Science (NIFS) to achieve the efficient transport control, high T_e plasma and high performance CW operation [8]. Based on these, 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 (Toshiba Electron Tube and Devices) [5, 6, 9]. These frequency ranges are also important for advanced magnetic fusion devices like spherical tokamaks, who use the EBW heating / current drive, and other low magnetic field devices. In the low frequency gyrotron, the control of diffraction loss is a key to open the CW operation with the 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.

2. Development of 77 GHz gyrotron for LHD

The 1 MW 77 GHz gyrotron development for LHD has been started from 2006 under the joint program between the NIFS and University of Tsukuba. The design parameters of the most recent 77 GHz tube (#3 tube) aiming at 1.5 MW output are shown in the right hand side of the Table 1. The several improvements have been taken into the tube as the feedback of the previous studies. In general, the major issues of the high power long pulse gyrotrons are the heat due to ohmic and dielectric loss, collector loss and diffraction loss. Against these, $TE_{18,6}$ cavity, synthetic diamond window and depressed collector where the ITER gyrotron technologies are incorporated, are effective except the diffraction. In lower frequency tubes like 77 GHz or 28 GHz one, less convergence of the RF beam at the window as well as the diffraction (stray RF) are the key issues of the design due to larger wavelength. One of the reasons of the diamond window crack in the first tube was the diffraction and the lack of the convergence [5, 10]. Both first and second tubes (#1 & #2) demonstrated the 1 MW for 5 s but their CW operations were limited to 1 min at 300 kW due to out-gassing by the some internal component local heating. In

	28GHz Gyrotron for PRC(Tsukuba) E39200	77GHz Gyrotorn for LHD(NIFS) E3988		
Frequency	28GHz	77GHz		
Output Power	1MW	1.5MW	1.2MW	0.3MW
Pulse Width	1s	2s	10s	CW
Output Efficiency	35% (W/O CPD)	50% (with CPD)		
Beam Voltage	80kV	80kV		
Beam Current	40A	60A		
MIG	triode	triode		
Cavity mode	$TE_{8,3}$	$TE_{18,6}$		
Mode Converter	Built-in	Built-in		
Output mode	Gaussian like	Gaussian like		
Output Window	Sapphire Aperture ϕ 112mm	CVD Diamond Aperture ϕ 89mm		
Collector	W/O CPD I.D.320mm Sweeping coils	Depressed Collector I.D.320mm Sweeping coils		
Height	2413mm	3104mm		
Weight	~ 700kg	~ 800kg		

Table 1 Design parameters of 28 GHz and 77 GHz of over-1 MW output. CPD: Collector Potential Depression.

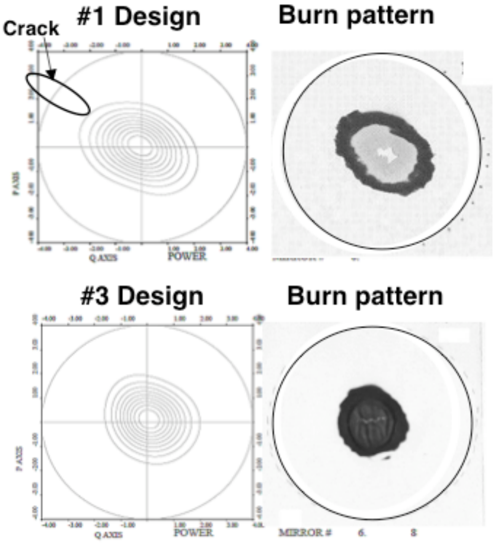

Fig. 1 The calculated beam patterns (left) and experimentally obtained burn patterns (right) at the window of the #1 tube(the top) and those of the #3 (the bottom).

addition, their power was limited by α (= $v_{\perp} / v_{/\!/}$) dispersion, which reduced the effective α in the operation.

In the third tube (#3), internal mode converter and mirrors are carefully designed to optimize the shape minimizing the electric field at the window edge and the diffraction loss, as shown in the Fig. 1. The maximum edge field is about 1/3 compared with the previous ones. The crack position is indicated in the top of Fig. 1. The elongated shape of the #1 beam is changed to be circular in the #3 (the bottom of Fig. 1). The result of the improvement is also seen in the burn patterns at the window shown in Fig. 1. At the same time, the diffraction loss up to the window is reduced from 3.3% to 2.5% by the design optimization.

The Magnetron Injection Gun (MIG) and cavity design of the #3 tube is improved to increase power more than 1.5 MW. As for the MIG design, to suppress the effective α decrease in high current, the cathode area is enlarged by 32% and the laminar flow has been improved by the deeper angle of the cathode plane. The current density along the beam flow has been lowered substantially and hence the reduction of the α dispersion and increase in effective α are expected by these improvements. The cavity Q is optimized for 1.5 MW with lower α extending the length of the cavity and is 987, 18% larger than previous. The short pulse output performances vs. collector current I_C of the #3 tube are shown in Fig. 2, comparing with previous ones. More than 1.5 MW output power (Po) at MOU (Matching Optics Unit) has been obtained. The maximum efficiency experimentally obtained is ~ 50% at 640 kW with depressed collector operation (CPD) and 34% without CPD.

After 1 MW short pulse test in Tsukuba gyrotron test stand, the tube was moved to NIFS and has been tested in LHD ECH system. As the result of the design improvement, we have obtained the 1.8 MW for 1 s even in the soft excitation mode [11]. Fig. 3 shows the 1.5 MW, 1.5 s operation in the LHD gyrotron system. The output power decreases gradually, corresponding to the beam current decrease due to the cathode cooling. The maximum duration with 1.9 MW, 1.8 MW, 1.6 MW, 300 kW and 200 kW are 0.1 s, 1 s, 1.8 s, 40 min and 75 min, respectively. The three tubes (#1- #3) have been installed into LHD ECH system. Total of more than 3 MW has been injected into the LHD plasma and produced the 15 keV electron temperature plasma [12]. They also have contributed to the long pulse operation of LHD.

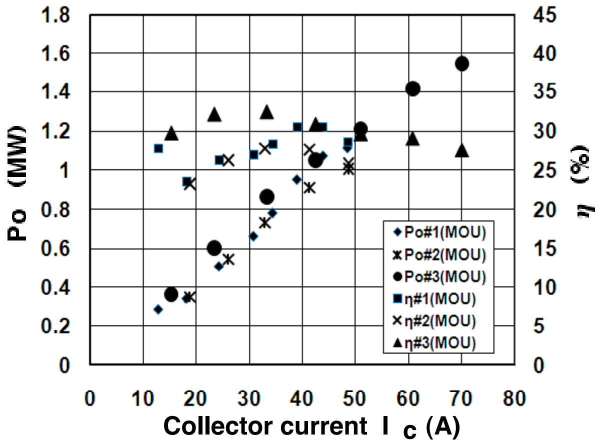

Fig. 2 The comparison of the experimentally obtained output performances (output Po and efficiency η in short pulse) among the three gyrotrons. The #3 whose electron beam and cavity design was improved has the best performance.

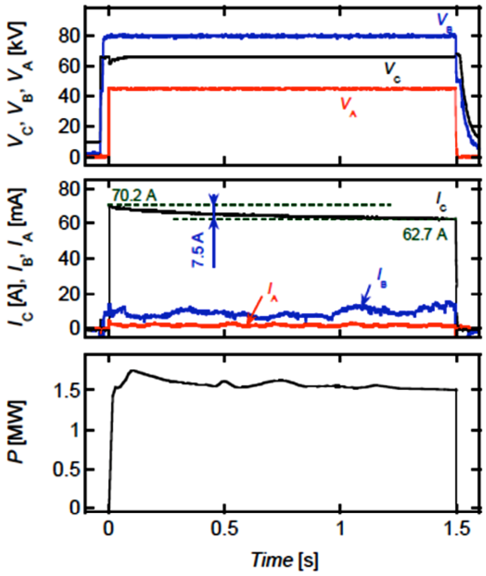

Fig. 3 Time evolutions of output power P, the collector current Ic, the cathode -collector voltage Vc in the operation of 1.5 MW for 1.5 s.

3. Development of 28 GHz gyrotron for GAMMA10 ECH system

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 the experiences of both 28 GHz 500 kW and 77 GHz 1 MW tubes in close collaboration with JAEA, NIFS and TETD. The design parameters are shown in the Table 1. The picture of the 28 GHz gyrotron is shown in Fig. 4. The MIG design of the 1 MW tube employs the triode gun to have flexibility of the α control by the 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. $TE_{8,3}$ mode has been chosen as the cavity mode, from the consideration of the 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 gyrotron is far more important than the 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. The calculated result of the RF beam profile at the window is shown in Fig. 5. The discussion of the diffraction loss will be done later.

The short pulse experiment of the fabricated 28 GHz 1 MW gyrotron has been carried out using the #3 LHD SCM, since both GAMMA 10 and LHD tubes are designed to use similar magnetic field profile. At first, the burn pattern and frequency were measured. The centrally peaked burn pattern was obtained and is consistent with Fig. 5. The oscillation frequency is 28.04 GHz which is expected from the cavity design. From these, oscillation mode of $TE_{8,3}$ is confirmed. The experimental output power and efficiency are shown in Fig. 6. The power of more than 1 MW has been obtained at 40 A beam currents and

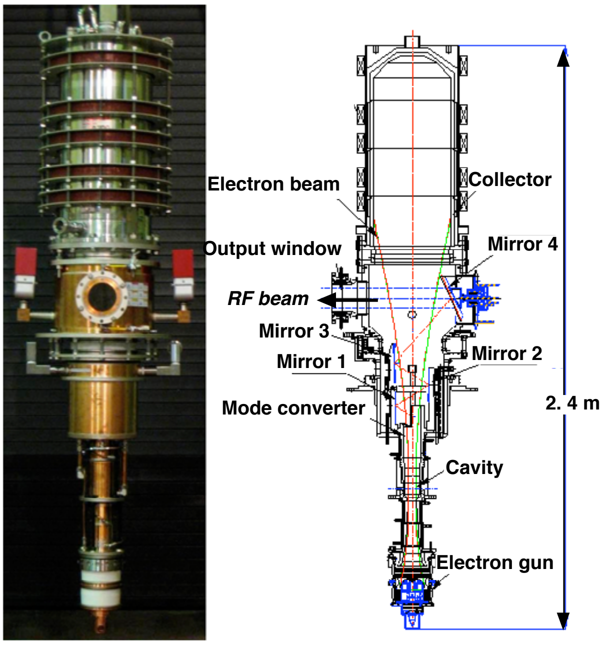

Fig. 4 Picture and schematic cross-section of 28 GHz 1 MW gyrotron for GAMMA 10.

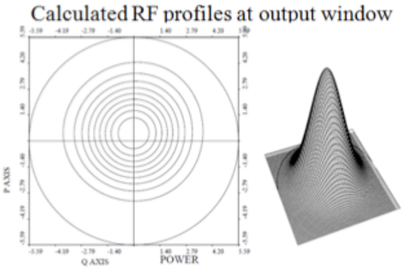

Fig. 5 Calculated RF beam profile at the window of the 28 GHz 1 MW gyrotron.

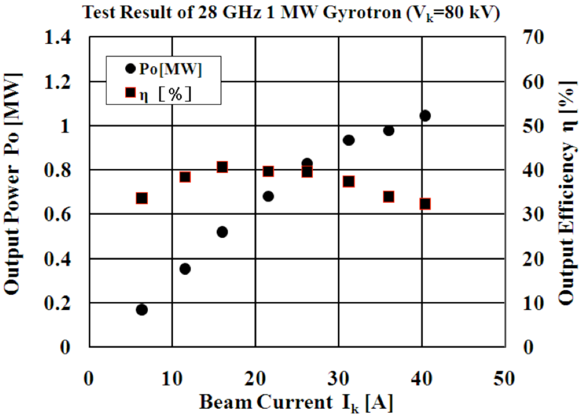

Fig. 6 Experimentally obtained Output power and efficiency of 28 GHz 1 MW gyrotron vs. collector(beam) current, where the #3 LHD SCM was used in the test. The maximum power of 1.05 MW was obtained.

the maximum efficiency of 40% around 20 A collector current. The comparison between the calculated and experimental output performances are shown in Fig. 7, where the 6 calculated cases from α = 1.0 to 1.5 are plotted. The calculated output of ~ 1.4 MW with 40 A is obtained with α = 1.2 and the efficiency is about 40% without CPD. The experimental collector current dependence of output power agrees with that of α = 1.4 – 1.5 in low current but it becomes to saturate in more than 25 A. In the actual operation, anode voltage and the gun field must be adjusted to get the maximum power at the same collector current. The estimated α value from these operation parameters become smaller in high collector current region. The obtained current dependence of output power is consistent with the calculation taking the actual α value estimated from beam parameters, which indicates the α decrease in the high current region.

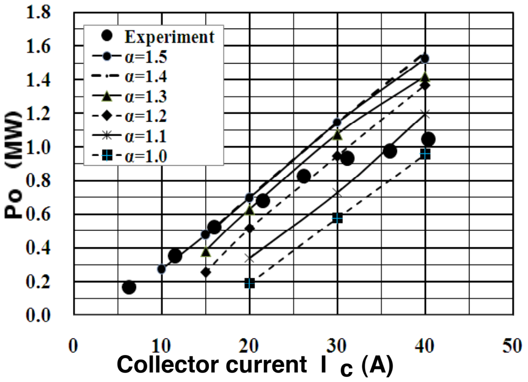

Fig. 7 Comparison between experimental and calculated output power of 28 GHz 1 MW gyrotron vs. collector(beam) current. Closed black circles indicate the experimental output. The other points are calculated output with α = 1.0 – 1.5.

The long pulse test of the 28 GHz 1MW tube has been carried out, using the #1 LHD SCM. As the first step, it has been done with 400 kW and obtained up to 1 s operation. The accumulated conditioning time for obtaining 1 s pulse duration is about 134 hours of the operation. After 150 ms duration, the speed of the conditioning was accelerated. The power of the present test was restricted due to the SCM operation capability. For the 1 MW long pulse test, finer tuning of the gun field is required, which is impossible with the #1 LHD SCM. 1 MW test will be done with the new SCM for 28 GHz gyrotron which is similar to the #3 LHD SCM. From the conditioning result of 400 kW, it is expected to get 1 MW for 1s operation soon.

As described before, the design of mode converter and mirrors are quite important. The sizes of the mode converter and mirrors normalized by the wavelength are relatively small in 28 GHz tube and thus causing significant diffraction losses. Hence, the optimal design of the mode converter is one of the important issues for high power, high efficiency and long pulse operations of low frequency microwave range gyrotrons. Figure 8 shows the calculated diffraction loss of various gyrotrons. The mode converter launchers of these gyrotrons had been designed by the use of the same optimization algorithm. *λ/D* is a ratio of wavelength to the initial radius of mode converter launcher.

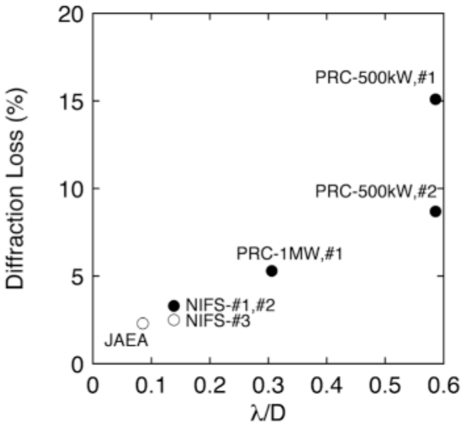

Fig. 8 Calculated diffraction loss vs λ/D. The diffraction loss roughly proportional to the λ/D, The quality of the mode convertor and mirror design is seen from this figure.

Since the JAEA ITER gyrotron has small wavelength (170 GHz, TE$_{31,8}$), the diffraction loss is quite small (2.3%), which enabled the operations of 1 MW for 800 s and 0.8 MW for 1 h [13, 14]. The calculated transmission efficiency is 99.5% from the launcher to the first parabolic mirror. The diffraction loss of NIFS-#1, #2 gyrotrons (77 GHz, TE$_{18,6}$ for LHD) is 3.3%, and 0.2 MW for 300 s and 1 MW for 5 s are achieved [10, 11]. That of the # 3 tube is improved to

2.5% and has achieved 0.2 M for 75min, as described in the section 2. In case of 28 GHz, the wavelength is 6 times larger than that of the ITER gyrotron. The diffraction loss is far larger than those of ITER and LHD tubes, as seen from Fig. 8. In case of the first 500 kW 28 GHz tube it has more than 15% diffraction loss [15]. In the 28 GHz 1MW tube, it is 5.3% by the optimization and larger D, where the D is maximized within the present SCM bore. In general, diffraction loss is proportional to the λ/D. It is found that the design of the launcher and mirrors of 28 GHz 1 MW gyrtoron has equal or even better quality compared with the ITER one, as seen from Fig 8. But the absolute value is still substantially larger than ITER one. To get better high power and long operation, we need more optimization of the launcher design with larger diameter and some other scheme to reduce the effect of the diffraction loss.

4. 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 the gyrotron is indispensable for this goal. For the upgrade of the GAMMA 10 and LHD performances, the joint program of NIFS and Univ. of Tsukuba to develop over-1 MW gyrotrons have been carried out in collaboration with JAEA and TETD. High power gyrotrons with $TE_{8,3}$ cavity at 28 GHz and with $TE_{18,6}$ cavity and a diamond window at 77 GHz have been developed for GAMMA 10 and LHD, respectively. The maximum outputs of 1.05 MW at 28 GHz and 1.9 MW at 77 GHz were obtained corresponding to each design. The operations of 1.8 MW for 1 s, 1.6 MW for 1.8 s, 0.3 MW for 40 min and 0.2 MW for 75 min were achieved in the #3 tube at 77 GHz, which are the new records of this frequency range tube. The operation of 1 s with 400 kW has been obtained in the long pulse test of the 28 GHz tube. More power would be expected with the optimized gun magnetic field. The stray RF is the major cause limiting gyrotron performance in lower frequency tubes. It is, therefore, essential for the design of the lower frequency gyrotron to reduce the diffraction loss. The comparison of the design quality for the reduction of the stray RF among the recent JAEA, NIFS and Univ. of Tsukuba gyrotrons. It is found that the quality of the mode converter design of 28 GHz 1 MW tube is almost limit of the design within the present geometry. It must be also pointed out that the some active schemes to extract stray RF in the gyrotron like sub-window with large diameter or use of the CPD DC ceramic for active RF extraction.

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