Development of Mega-Watt Gyrotrons for Fusion Research

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At the Plasma Research Center (PRC) in University of Tsukuba, development of Mega-Watt Gyrotrons is performed for fusion research. We are developing a new 28 GHz 1 MW and a 77 GHz 1.5 MW gyrotron for ECRH system of tandem mirror GAMMA10 and Large Helical Device (LHD), respectively. In the short pulse test of 77 GHz gyrotron, the maximum output power of 1.6 MW and the maximum total efficiency of 49.4% with CPD were obtained. In the long pulse test, the pulse length extended to 5 sec. with 1 MW and 4500 sec. with 0.2 MW. The design study of 154 GHz 1MW gyrotron for LHD has been started. For each cavity oscillation mode, $TE_{28,8}$, $TE_{28,12}$ and $TE_{31,8}$, cavity, electron gun (MIG), mode converter, collector and SCM design are being examined.

I. Introduction

The electron cyclotron heating (ECH) is important for tandem mirror devices to achieve potential confinement and high electron temperature. A gyrotron is a powerful and an essential tool for ECH. Recent progress of the gyrotron has widened the use of gyrotrons for fusion research in such as tandem mirror devices or toroidal magnetic confinement systems. High power and long pulse operations of the gyrotron and the efficient transmission of its output are quite important to achieve better plasma performances.

At Plasma Research Center (PRC) in University of Tsukuba, three 28 GHz 0.5 MW and two 28 GHz 0.2MW gyrotrons are being applied to GAMMA 10 plasma[1]. A new 28 GHz 1 MW gyrotron and three 77 GHz over 1 MW gyrotrons have been developed for ECH systems of GAMMA10 and Large Helical Device (LHD) in National Institute for Fusion Science (NIFS), under the joint program between NIFS and PRC with the collaboration of Japan Atomic Energy Agency (JAEA) and Toshiba Electron Tube & Devices Co.,Ltd. (TETD)[2]. In the initial test of the 28 GHz 1 MW tube with short pulse duration, the design target of 1 MW output power was achieved and high oscillation efficiency of 40 % was obtained[3]. In the development of 77 GHz gyrotron, the maximum output power of over mega-watt was achieved too.

This report describes the test results of 77GHz mega-watt gyrotrons. In addition, new design study of 154 GHz 1MW gyrotron for LHD is described.

II. Experiment of 77 GHz Gyrotron

A set of design parameters of the 77 GHz 1.5 MW #3 gyrotron is shown in Table1. The magnetic injection gun (MIG) is a triode gun. The $TE_{18,6}$ mode RF wave oscillated at the cavity is converted to a Gaussian-like beam by a built-in quasi-optical mode converter, and RF beam is transmitted by four pieces of mirror system to the outside of the tube through a CVD diamond window. The collector adopts collector potential depression (CPD) for efficiency enhancement and has the sweep coil to reduce heat load to the collector.

Two 77 GHz 1 MW gyrotrons #1 and #2 have been tested in 2007 and 2008 respectively. Typical achieved parameters of #1 and #2 gyrotrons until the end of 2008 are maximum MOU (matching optics unit) output power of 1.1 MW, maximum total efficiency 39.4% with CPD and long pulse operations of 0.8 MW 3.6 sec., 0.3 MW 60 sec. and so on. In consideration of #1 and #2 gyrotrons test results, the improvement of 1.5 MW (#3) tube design was performed for higher efficiency and higher power ECRH system. Three points of the design improvement for 1.5 MW tube are the MIG design for quality improvement of the electron beam, the cavity design for the higher oscillation efficiency and the mode converter and mirror design for improvement of the RF distribution at the output window and the reduction of the diffraction loss.

The 77 GHz 1.5 MW gyrotron #3 has been fabricated and tested in 2009. The comparison of beam current dependences of the experimental output power and the calculated output power of 77 GHz 1.5 MW gyrotron are shown in Fig.1. The experimental output powers shown by closed circles (NIFS test) and closed

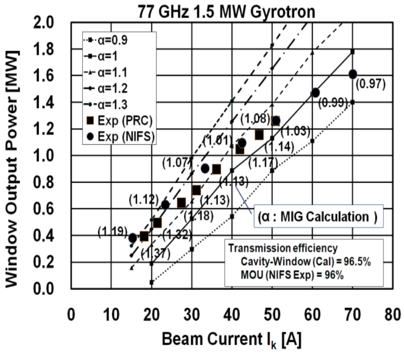

Fig.1 Comparison of beam current dependences of the experimental output power and the calculated output power of 77 GHz 1.5 MW gyrotron.

TABLE1. Design parameter of MW Gyrotron

	77 GHz Gyrotorn for LHD (NIFS)	154 GHz Gyrotron for LHD (NIFS)
Frequency	77 GHz	154 GHz
Output Power	1.5 MW 0.3MW	1 MW 0.3 MW
Pulse Width	2 s CW	5 s CW
Output Efficiency	50% (with CPD)	50% (with CPD)
Beam Voltage	80 kV	80 kV
Beam Current	60 A	60 A
MIG	triode	triode
Cavity mode	$\mathrm{TE}_{18,6}$	$\mathrm{TE}_{28,8}$ or $\mathrm{TE}_{31,8}$
Mode Converter	Built-in	Built-in
Output mode	Gaussian like	Gaussian like
Output Window	CVD Diamond	CVD Diamond
Collector	Depressed Collector Sweeping coils	Depressed Collector Sweeping coils

TABLE2. Achieved Parameter of 77GHz Gyrotrons

No.	Design	Short Pulse Operation	Long Pulse Operation
#1	1MW/5s 0.3MW/CW	1.11MW/33.9%(28.6%)/4ms 1.07MW/39.4%(30.5%)/4ms	1.03MW/32.8%(24.6%)/5s 0.31MW/33.1%(24.8%)/150s 0.13MW/20.6%(15.4%)/935s
#2	1.2MW/5s 0.3MW/CW	1.06MW/(27.5%)/1ms 0.75MW/36.6%(28.4%)/4ms	1.10MW/29.6%(24.1%)/1.2s 1.02MW/30.2%(24.6%)/5s 0.2MW/19.3%(15.1%)/370s 0.11MW/9.6%(8.2%)/1800s
		Anode Voltage Control	1.31MW/38.2%(26.7%)/1s
#3	1.5MW/2s 1.2MW/10s 0.3MW/CW	1.55MW/34.0%(27.6%)/4ms 0.64MW/49.4%(28.4%)/2ms	1.60MW/36.6%(29.7%)/0.5s 1.53MW/36.5%(29.7%)/1.6s 0.91MW/40.7%(33.1%)/1.8s 0.22MW/32.4%(24.3%)/4500s

square (PRC test) increase with the increase of beam current I_k. The maximum output power of 1.6 MW and the maximum total efficiency of 49.4% were obtained with short pulse duration. The calculations are adjusted by the calculated cavity oscillation power with each pitch factor α (= perpendicular velocity to the magnetic field / parallel velocity) of 0.9~1.3, the calculated transmission efficiency of 97.5% from the mode converter to the window. The calculated power increases with the α increase and does not saturate up to α=1.3. On the other hand, the experimental output powers have tendency to be saturated at the higher I_k. The electron beam may have α=1.3 around I_k~20 A. The pitch factor α decreases with the increase of I_k, and may become less than α=1.0 at I_k>60 A. In Fig.1, the values of round brackets are the pitch factor α calculated by MIG simulation code with the experimental operation parameters of both the PRC and the NIFS test. The similar dependence of α decrease with increase of I_k is seen by MIG calculation results, too. To avoid the α decrease and α spread increase in high beam current is one of the keys for the high power and the high efficiency gyrotron development.

The main achieved parameters of the #1, #2 and #3 gyrotrons are shown in Table2. In the long pulse operation, the output power and efficiency of #3 were improved largely in comparison with #1 and #2. Both the maximum output power of 1.6 MW with pulse width of 0.5 sec. and the maximum total efficiency of 49.4% with that of 2 ms were obtained in the #3 gyrotron results. The other achieved long pulse parameters were 1 MW 5sec., 0.2 MW 4500 sec. and so on. On the #2 gyrotron operation of 0.2 MW, limitation of the pulse duration was observed around the pulse width of 300 sec. because of sudden outgassing. The cause of this outgassing is regarded as the heating of the DC break section by the stray RF which is caused by a transmission loss. On the operation of the #3 tube which has the improved designs of mode converter and mirrors, the sudden outgassing has not been observed in 0.2 MW 4500 sec.

Ⅲ. 154 GHz Gyrotron Design

New design study of 154 GHz 1MW gyrotron has been started for second harmonics heating of LHD. A set of design parameters of the 154 GHz gyrotron is shown in Table1. The design targets of the output power are 1 MW 5 sec. and 0.3 MW CW. We consider the design that the 154 GHz gyrotron will have the compatibility with the 77 GHz gyrotron on the fabrication and be operated by using the same superconducting magnet (SCM). The magnetic field distribution used for the design is a tentative distribution by the under studying SCM, but that is possible for the 77 GHz gyrotron operation. As for the cavity oscillation mode, $\mathrm{TE}_{28,8}$, $\mathrm{TE}_{28,12}$ and $\mathrm{TE}_{31,8}$ mode are examined. The cavity mode will be decided by the total results of oscillation efficiency, cavity heat load, electron gun design, mode converter design, collector design, and so on. The magnetron injection gun (MIG) designs for $\mathrm{TE}_{28,8}$ and $\mathrm{TE}_{28,12}$ mode are identical because both electron beam injection positions at the cavity resonator are the same. An example of the MIG design for $\mathrm{TE}_{28,n}$ mode is shown in Fig.2. The 77 GHz gyrotron MIG can work for 154 GHz $\mathrm{TE}_{28,n}$ mode MIG with a good laminar flow beam. As showing in the anode voltage dependences of the pitch factor α and α spread, the desired α of 1.1 has been obtained with low α spread at the beam voltage of 80 kV and the anode voltage of 41 kV. As the mirror ratio of the magnetic field for $\mathrm{TE}_{31,8}$ must be smaller than that of 77 GHz and 154 GHz $\mathrm{TE}_{28,n}$ mode because the electron beam injection point at the cavity is outer side, enough alpha isn't obtained for $\mathrm{TE}_{31,8}$ mode. The design optimization of anode and cathode shape is necessary for $\mathrm{TE}_{31,8}$ mode.

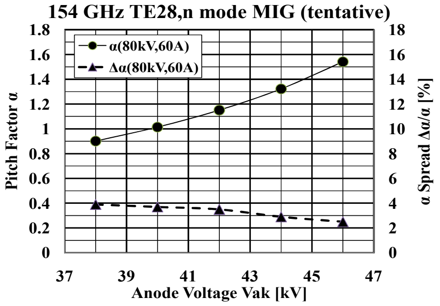

Fig.2 Anode voltage dependences of the calculated pitch factor α and α spread of 154 GHz $TE_{28,n}$ mode MIG.

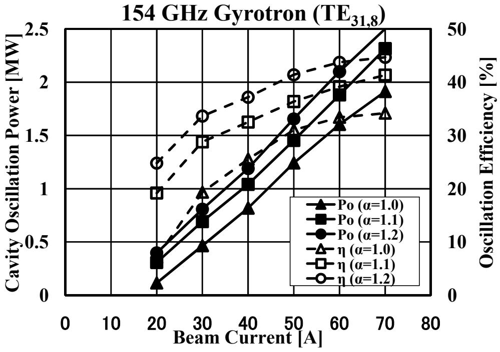

Fig.3 Beam current dependences of the cavity oscillation power and efficiency for 154 GHz $TE_{31,8}$.

TABLE3. Cavity design of 154 GHz gyrotron

Vk=80kV, Ik=50A		Oscillation Power	Oscillation Efficiency	Heat Load [kW/cm2]
TE31,8	α=1	1.241	31.03	1.31
	α=1.1	1.454	36.36	1.48
TE28,8	α=1	1.196	29.9	1.15
	α=1.1	1.456	36.41	1.5
TE28,12	α=1	1.125	28.12	0.8
	α=1.1	1.351	33.79	1.05

Beam current dependences of the cavity oscillation power and efficiency with each alpha of 1.0, 1.1 and 1.2 for 154 GHz $TE_{31,8}$ are shown in Fig.3. An oscillation power of 1.24 MW with the oscillation efficiency of 31 % is obtained at beam voltage V_k=80kV, beam current I_k=50A and α=1.1. The comparison of cavity oscillation power, efficiency and heat load for $TE_{28,8}$, $TE_{28,12}$ and $TE_{31,8}$ mode are shown in Table3. These results show that the output power of over 1 MW can obtain for each mode even if the RF transmission loss of a built-in quasi-optical mode converter and inner mirrors are considered. The $TE_{28,12}$ mode has smaller heat load than the other mode, but the efficiency is rather lower and the potential depression at the cavity is bigger. So the $TE_{28,12}$ mode will not select as the cavity mode.

The design of the collector is to control the electron beam trajectory and reduce the heat load by the optimization of the magnetic field distribution produced by the SCM and the collector sweeping coil. When considering the length limitation by the manufacturing-facility, the gyrotron window position and the design of collector sweeping coil, the electron beam injection point without collector sweeping coil is desired at 1300~1400 mm from cavity resonator center. The collector design for $TE_{31,8}$ mode is possible by the simple SCM which has the magnetic distribution to operate the 77 GHz gyrotron. In the operation of both the 154 GHz $TE_{28,n}$ mode and the 77 GHz gyrotron, the SCM design will be more complicated and its cost will be higher than $TE_{31,8}$ mode SCM.

Ⅳ. SUMMARY

The third 77 GHz tube for NIFS LHD device has the improved design for the power up to 1.5 MW. The maximum output power of 1.6 MW and the maximum total efficiency of 49.4% were obtained with short pulse duration. The long pulse test of two 77 GHz 1 MW and one 77 GHz 1.5 MW gyrotrons have been performed. The pulse width extended to 5 sec. with 1 MW and 4500 sec. with 0.2 MW. The limitation of the pulse duration which was caused by the stray RF heating has been improved by the design change of the mode converter and the mirrors of the 1.5 MW #3 gyrotron.

The design study of new 154 GHz 1MW gyrotron for LHD has been started. When we chose $TE_{28,8}$ mode as cavity oscillation mode, MIG design can be compatible with 77 GHz tube. In addition, the distance between the electron beam and the radiator/mirrors is bigger than the case of $TE_{31,8}$ mode. The $TE_{31,8}$ mode is better than $TE_{28,8}$ mode from the design point of collector and SCM. It was shown by cavity simulation that the output power of more than 1 MW is possible for each cavity mode. The cavity oscillation mode and the magnetic field distribution design of SCM will be decided and the detail design of gyrotron will be performed in near future.

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