Development of 1MW Gyrotron and Progress of ECH System for the GAMMA 10 Tandem Mirror in Tsukuba

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Abstract. High power gyrotrons with $TE_{4,2}$ 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 in the joint program of NIFS and University of Tsukuba. The maximum outputs of 570 kW at 28 GHz and 1.1 MW at 77 GHz were obtained corresponding to each design. The operations of more than 750 kW for 5 sec. and 810 kW for 3.5 sec. were achieved in the developing tubes at 77 GHz, which is the first high power-long pulse result of the 77 GHz tube. The experimental simulation of the effect of the stray RF in the 28 GHz tube indicates the stray RF is the one of the major causes limiting gyrotron performance. The output of more than 1 MW with 40% oscillation efficiency is expected from the design of the next 28GHz gyrotron for GAMMA 10. Installation of the polarizer in the transmission line enhanced the performance of the ECH system in GAMMA 10, that is the first result which clearly showed ~100% X mode excitation is a key to design the efficient fundamental ECH system of strong field side injection in mirror devices.

1. Introduction

An ECH is a reliable and attractive tool for the plasma heating, the current drive and the plasma control like NTM suppression in the magnetic confinement fusion devices. The 1MW gyrotron at 170 GHz for the ITER ECH system has been developed for more than 10 years [1] and it demonstrated 1 MW CW performance, recently [2]. In GAMMA 10 tandem mirror, the ECH system has been installed from the beginning, since it is essential for the tandem mirror devices to achieve high confining potential, high electron temperature and transport control by the ECH. In the last 20 years, the ECH power sources of the GAMMA 10 were 200 kW gyrotrons at 28 GHz. From power scaling of confining potential, higher the ECH power is, stronger the potential formation. The GAMMA 10, therefore, has started the ECH upgrade program [3] in collaboration with Japan Atomic Energy Research Institute (JAEA) who is developing the ITER 170 GHz tube [1, 2]. As the first step, a 28 GHz 500 kW gyrotron, and the high performance transmission line and antenna have been developed. We applied them to the GAMMA 10 and new record of the ion confining potential of more than 2 kV has been achieved [3]. The ECH is an important tool of the plasma control for LHD in National Institute for Fusion Science (NIFS) through the precise control of the current and pressure profiles. New 1 MW gyrotrons are required for this purpose in LHD [4]. Based on these back ground, a MW tube project has started as the joint program between NIFS and Univ. of Tsukuba to develop 1 MW tubes of 77 GHz for LHD and 28 GHz for GAMMA 10 in collaboration with JAEA and TETD (Toshiba Electron Tube and Devices). The gyrotrons with frequency ranges of these tens GHz are important for advanced magnetic fusion devices like spherical tokamaks, too. From the viewpoint of the simple ohmic and dielectric loss, lower frequency tube is less difficult to develop but the difficulty is in the larger wavelength, which makes the diffraction loss more in the tightly limited dimensions of gyrotrons.

2. Development of high power gyrotron

2.1 500kW, 28 GHz gyrotron development and study of stray RF

The heart of the ECH system is a gyrotron. As the first step of the GAMMA 10 ECH upgrade, the development of 500 kW gyrotron from the previous 200 kW was carried out. The design parameters are listed in the TABLE 1, comparing the two gyrotrons. The difficulty of this development was in the restriction of the electron gun size because of using the same magnet of the 200 kW tube [5]. A diode type gun was employed to decrease the current density of the cathode. The tube successfully showed the maximum output of 570 kW with efficiency of ~ 40%. Because of the diode gun, it was sometimes difficult to operate in long pulse. We installed the large series register to reduce the body current in case of the gyrotron flash over and became to show better and better performance. The developed 500kW gyrotrons have been used for the formation of the ion confining potential in the plug cell and the electron heating of the central cell in the GAMMA 10. It is observed the confining potential and electron temperature increase with injected power up to the maximum of the present limit.

TABLE 1 DESIGN PARAMETERS OF GYROTRONS

	Previous tube	Upgrade tube	LHD tube	Next design
Frequency	28 GHz	28 GHz	77 GHz	28 GHz
Power / Pulse Length	200kW /0.075 s	0.5MW/0.1 s	1MW / 5 s 0.3 MW/CW	1MW/0.5 s
Beam Voltage	75 kV	75 kV	80 kV	75 kV
Max. Beam Current	8 A	20A	50A	45A
Electron GunType	Triode	Diode	Triode	Triode
Cavity Mode	$TE_{0,2}$	$TE_{4,2}$	$TE_{18,6}$	$TE_{8,3}$
Output Window	Alumina	Alumina	Diamond	Sapphire
Output mode	$TE_{0,2}$	Gaussian	Gaussian	Gaussian

Toward the development of the next step gyrotron for the high power and long pulse operation, it is extremely important to reduce the diffraction loss in the gyrotron with an internal mode converter for both efficiency enhancement and stray RF reduction. But it is inevitable to have several percent diffraction which corresponds to tens of kW for a MW tube. This power becomes stray RF and affects many sub-components yielding the limit of operation and sometimes causes crucial damage of the tube. The most critical ones are against the gyrotron inner components. It heats the cathode, changes the emission and makes the gyrotron unstable. It sometimes heats up the small minor component gradually and finally yields the large outgassing which limits the long pulse operation of the

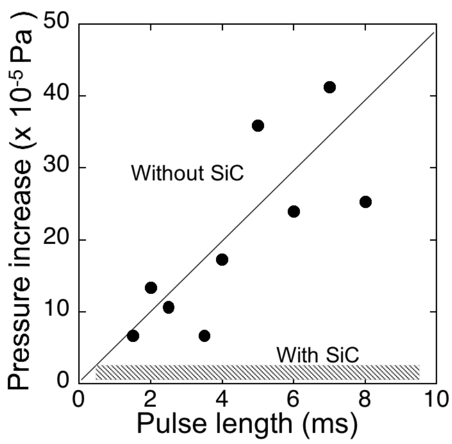

Fig. 1 Pressure increase of the MOU with(shaded region) and without SiC absorber(closed circles).

gyrotron. The accumulated RF causes the discharge in gyrotron and increases the pressure and gives the damage to the some inner components or even to the window. Outside the gyrotron, it has also possibility to cause break down at the junction of the waveguide like miter bends. In this sense, the reduction of the stray RF in the gyrotron is extremely important.

To simulate the effect of the stray RF in gyrotron, we studied the effect of the stray RF in MOU (Mirror Optics Unit) of a 28 GHz gyrotron. The figure 1 shows the pressure increase with and without the SiC absorber in the MOU during the high power transmission of 380 kW. The diffraction power in gyrotron becomes stray RF and most of it flows into the MOU, since the ohmic loss is very small due to the Cu inner surface of the gyrotron. The stray RF from the gyrotron causes the local RF discharge which increases in the pressure of the MOU, as indicated with closed circles in Fig. 1. The pressure of the MOU increases with the injected pulse length in the case of without SiC. It is suppressed with the SiC absorber placing in the MOU. We also observed the traces of the break down at edge of the miter bend, but they are suppressed after the reduction of the stray RF in the transmission line. These results indicate the importance of the stray RF reduction.

2.2 Development of 1MW 77 GHz gyrotron

As the second step, Tsukuba-NIFS joint development program of 1 MW 77 GHz gyrotron for LHD has started. The design parameters of the 77 GHz tube are shown in the TABLE 1. The major issues of the tube are the heat due to ohmic and dielectric loss, collector loss and diffraction loss mentioned above. $TE_{18,6}$ cavity, synthetic diamond window and depressed collector, making use of ITER gyrotron technologies are effective against these kind of heat problems 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. The well-managed design of the internal mode converter and mirrors minimized the diffraction and beam size at the window.

The design of the in-waveguide mode converter was carried out using the code to calculate the electric field profile on the edge of the radiator to reduce diffraction loss, optimizing the surface perturbation [6]. The design of the mirrors was also optimized to reduce the stray RF and beam edge field. The diffraction is 3.3 % and the electric field at the edge of the window is less than -25dB of the center field. The calculated power profile at the window is shown in Fig. 2(a) and compared with

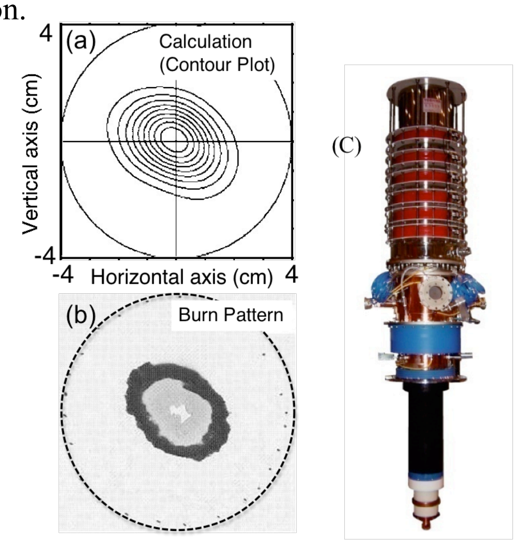

Fig. 2 (a) The calculated power profile and (b) the experimentally obtained burn pattern at the window. (c) The picture of 1 MW, 77 GHz gyrotron.

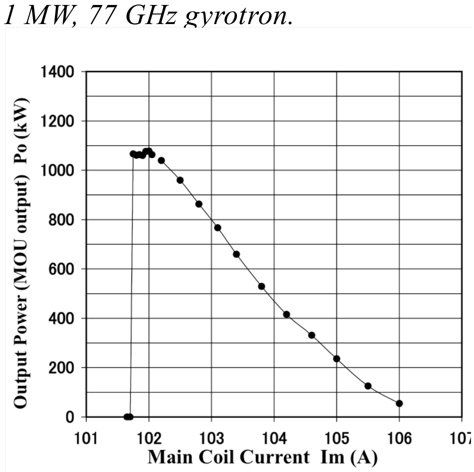

Fig. 3 The output power vs the main field coil current of #1 tube, with Vk = 80kV and Ic=48.7A. f = 76.97 GHz.

the experimentally obtained burn pattern of the first 77 GHz (#1) gyrotron (Fig. 2(b)). They both agree well. The measured frequency of 76.95 - 76.98 GHz and output performance against the main magnetic field shown in Fig. 3 indicate the excited mode was the $TE_{18,6}$ normal mode. The figure 4 shows the output power against the beam currents. The #1 tube has achieved 1.1 MW at the MOU output with 48.7 A beam currents in short pulse. The maximum efficiency obtained experimentally is about 30%, which is less than the value expected from the calculation (36 %), which indicates the pitch facer α (ratio of the perpendicular and parallel velocities of the electron beam) is limited to be smaller than designed. The maximum total efficiency with energy recovery (CPD) is 39.3%.

After the confirmation of 1 MW output of the #1 tube, conditioning of the tube was carried out by increasing the pulse length gradually, monitoring the RF waveform, ion pump pressure, and temperatures of the various points, carefully. Pulse repetition period was controlled with keeping the duty almost constant. The long pulse operation of 460 kW for 5 s was quickly obtained with the conditioning of just 65 hours (heater time), as shown in Fig. 5. But the operation of #1 tube was limited at 810 kW for 3.5 s due to the crack of the window.

The crack position of the diamond disc is shown in Fig. 6 with the arrow. It is at the edge of the disc and the azimuthal angle is near the elongated direction of the RF beam which is shown in Fig. 2 (a) and (b) (left top). From the simple estimation of the thermal stress due to the dielectric loss of the calculated field profile at the window, it never causes the crack. It is not clear what is the main cause of the crack. One of the possibilities is accumulation of the stray RF and/or the beam edge field near the peripheral metal-diamond interface of the window. To avoid this kind of possibility in the second tube, the effective inner diameter of the cylinder sleeve of the window has been cut down by 5 mm and the thin TiO_2 coating on the outer surface of the sleeve in the MOU side has been done. We have also made the gap between the sleeve edge and the diamond disc as small as possible.

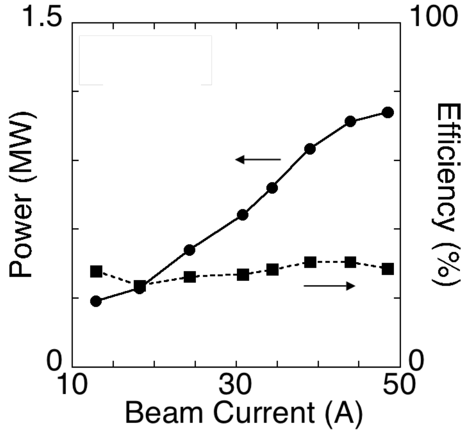

Fig. 4 The output power and the efficiency vs beam currents of the 77 GHz first tube.

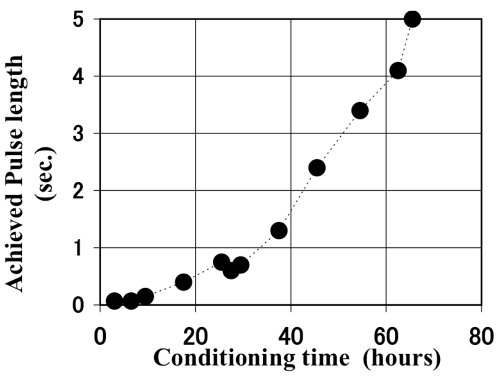

Fig. 5 Pulse extension result with 460 kW. Achieved pulse length against the conditioning time.

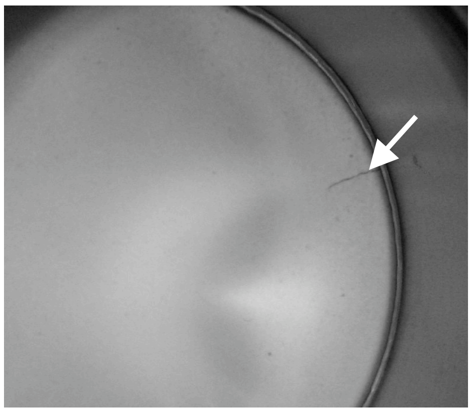

Fig. 6 The crack of the window edge indicated by the arrow. The diamond window is viewed from the vacuum side of the gyrotron, while the patterns in Fig. 2(a) and (b) are viewed from the MOU side. .

The second tube which took the feedback from the results of the first tube has been fabricated and is now under testing. The Short pulse performance is similar to the #1 tube and the output of I MW has been obtained. The power of more than 750 kW for 5 s has been also achieved quickly. The figure 7 shows the time evolution of the wave forms of the body, collector and anode voltages, the collector and anode currents and the power received with the long pulse dummy load of the #2 tube during the 5 sec. operation with an average power of ~ 750 kW at the MOU output. The collector current is 50.5 A at the beginning and decreases gradually to 43.9 A during 5 second. The short declines of the power and currents near the end of the pulse occurred due to the interlock against the abnormal oscillation. We are now carefully extending the pulse length and the power level to obtain 1MW for more than 5 seconds.

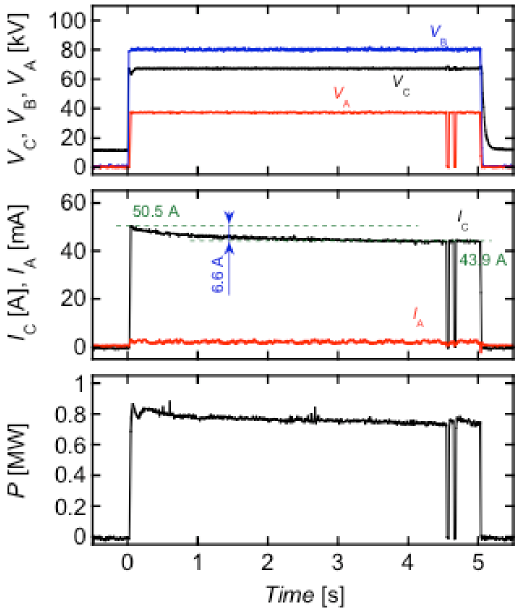

Fig. 7 Time evolution of the collector, body and anode voltages, the collector and anode currents and the power measured with a long pulse dummy load during 5 second operation with 750 kW level output.

2.3 Design of 1 MW 28GHz gyrotron for GAMMA 10

The new 1 MW, 1 sec., 28 GHz gyrotron development for GAMMA 10 ECH source has started, based on the experiences of both 28GHz 500 kW and 77 GHz 1MW tubes in addition to the ITER 170 GHz tube. The design parameters are shown in the TABLE 1. The cavity mode has been chosen as $TE_{8,3}$, from the consideration of the ohmic loss, electron beam density and beam size. The triode gun of MIG (Magnetron Injection Gun) type is employed,

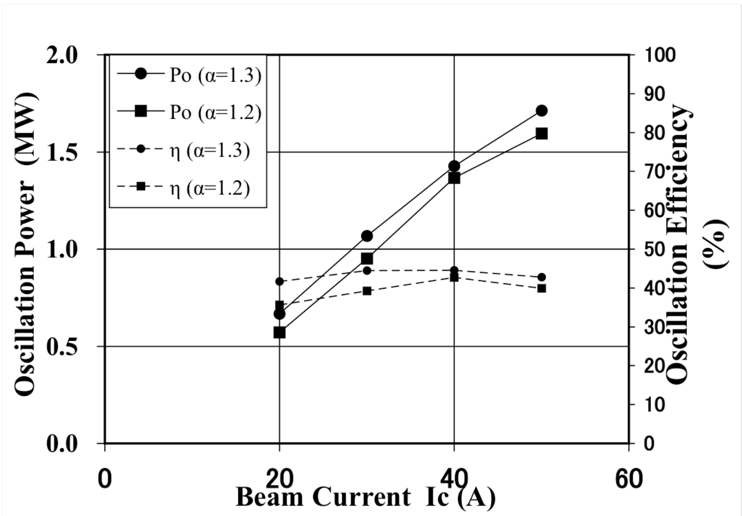

Fig 8 The calculated output performances of 28 GHz, 1MW gyrotron.

since the operation flexibility of the α is important to get higher performance. The window material is Sapphire with the aperture diameter of 112 mm. Using the same design code of ITER gyrotron, cavity has been designed. The calculated output performances are shown in the Fig. 8, where power and efficiency in the two cases of a = 1.2 and 1.3 are plotted. The output power of ~ 1.4 MW with 40 A is obtained in the case of α = 1.2. The oscillation efficiency is about 40 % without CPD. From the MIG simulation code, the beam α spread (Δα/α) about 3 % is obtained with α = 1.2 ~ 1.3 in case of 40 A beam currents.

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 higher frequency one, as mentioned in the section 2. An example of the field pattern at the first mirror radiated from the mode converter is shown in Fig. 9, using the code mentioned in the section 2.2 [6]. Using this field pattern, transmission efficiency of the RF beam from cavity to the window is 94.4 %. The efficiency is improved substantially from the previous 28GHz, 500 kW tube (88 %). The design still has ~5 % diffraction loss due to lower frequency.

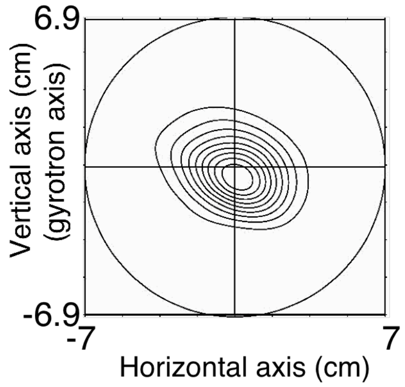

Fig. 9 The field pattern at the first mirror calculated from the radiated field from the designed mode converter.

3. Improvement of Transmission Line and Antenna for GAMMA 10

Improvement of the antenna for the electron heating of the central cell of the GAMMA 10 has been carried out to make the absorption profile axisymmetric and peaked and to increase the transmission efficiency[7]. In the past years, the Vlasov type radiator was used to irradiate microwave power to the plasma. In recent years, the antenna has been replaced with the two concaved ellipsoidal mirrors as shown in Fig. 10, which improved transmission efficiency remarkably. The efficiency from the antenna to the resonance surface within the radius of 5 cm from the center axis has been increased from ~ 20 % to

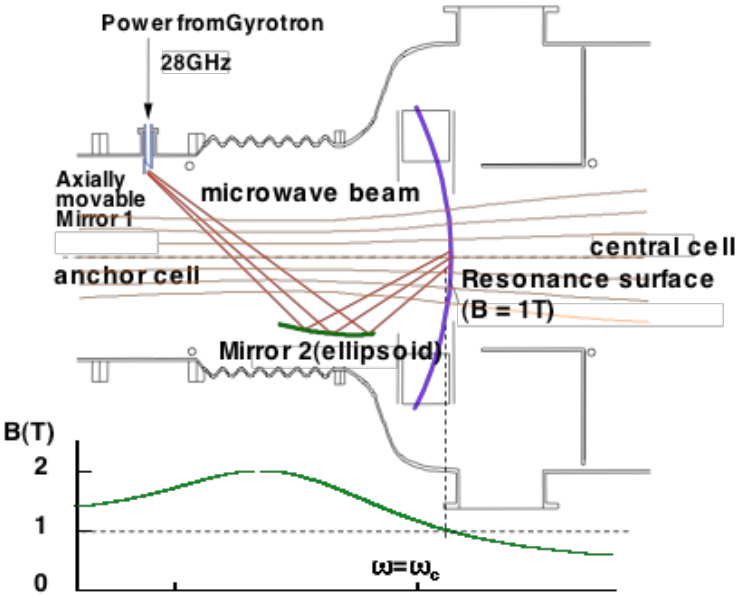

Fig 10 The mirror antenna system of the central ECH on the GAMMA 10. The microwave power is launched from the top and transmitted to the resonance surface through two focusing mirrors.

-70 % in the calculation. The heating effect, correspondingly, becomes improved [3].

Since the output microwave from gyrotron is linearly polarized, a polarizer is indispensable to increase X mode fraction for efficient heating in the fundamental X mode heating with the oblique incidence. The polarizer is composed of two grooved mirrors (twister and polarizer mirrors) and can generate almost all combination of elliptic polarization. Figure 11 shows the time evolutions of the diamagnetism in the shots with various X mode fractions with the gyrotron power of 200 kW. The central ECH was turned on from 160 ms. It is seen that the diamagnetic signal increases with the high X mode fraction but decreases with the low X mode fraction. The change in the diamagnetic signal against the X mode fraction during the ECH with 100 kW gyrotron power is shown in Fig12. As expected from theory, it is clearly confirmed the wave which contains more X mode shows better heating effects. It is seen high O mode fraction deteriorates the heating. This is the first result which shows clearly the importance of the pure X mode excitation in the design of the fundamental ECH system injecting from high field side in mirror devices.

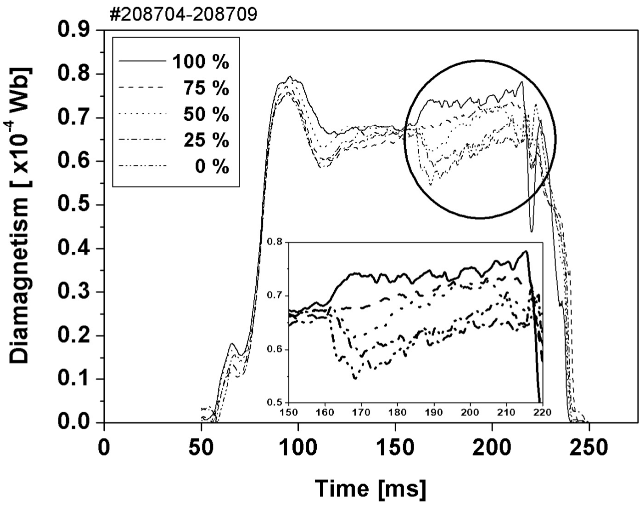

Fig. 11 Time evolutions of diamagnetic signals with different X mode fractions ECH. The enlarged waveforms during the ECH pulse are also shown together.

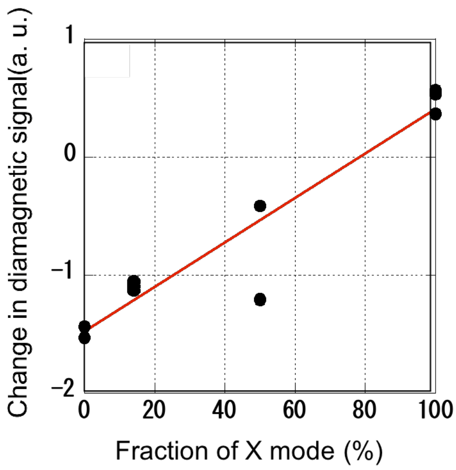

Fig.120 Change in the diamagnetic signal from the value before the ECH vs X-mode fraction.

4. Summary

The gyrotron is the heart of the ECH system. For the upgrade of the GAMMA 10 and LHD ECH systems, the joint program of NIFS and Univ. of Tsukuba to develop 1 MW gyrotrons are going on in collaboration with JAEA and TETD. High power gyrotrons with $TE_{4,2}$ 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 570 kW at 28 GHz and 1.1 MW at 77 GHz were obtained corresponding to each design. The operations of more than 460 kW for 5 sec. and 810 kW for 3.5 sec. were achieved in the first tube at 77

GHz, which is the first high power-long pulse result of 77 GHz tube. The first tube test was interrupted due to the window crack. The second tube which took the feedback from the first one has achieved more than 750 kW for 5 seconds and is under testing for further high performance. The stray RF is the one of the major causes limiting gyrotron performance. It is, therefore, essential for the design of the lower frequency gyrotron to reduce the diffraction loss. Installation of the polarizer in the transmission line enhanced the performance of the ECH system in GAMMA 10, that is the first result which clearly showed ~100% X mode excitation is a key to design the efficient fundamental ECH system injecting from the high field side in mirror devices.

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