1-7 Development of frequency tunable gyrotrons for plasma diagnostics

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Development of two types of frequency tunable gyrotrons are described. One is frequency step-tunable gyrotrons (Gyrotron FU Series) which cover wide range from millimeter to submillimeter wavelegth region. The other is a quasi-optical gyrotron operating in 90 and 180 GHz bands. Both are applicable for plasma diagnostics as power sources.

1. Introduction

The development of gyrotrons is proceeding in two directions. One is the development of high power, millimeter wave gyrotrons as the power sources for electron cyclotron heating of plasmas and electron cyclotron current drive of tokamaks and for industrial technologies, for example, ceramic sintering. The second direction is the development of high frequency, medium power gyrotrons as millimeter to submillimeter wave sources for plasma scattering measurements, ESR experiments and so on.
Gyrotrons developed in Fukui University, under cooperation with University of Sydney and National Institute for Fusion Science belong to the second group. High frequency, medium power gyrotrons covering a broad frequency band in millimeter and submillimeter wavelength regions have been developed. 'Gyrotron FU series' consisting of 8 gyrotrons has many achievements including frequency tunability from 38 GHz to 889 GHz, high harmonic operations up to the fourth harmonics, studies of mode competition and mode cooperation, high purity mode operation, frequency and amplitude modulations, frequency step switching, complete cw operation for a long time (≧15 hours), high stabilization of the amplitude by feed back control of anode voltage of electron gun and so on.
A quasi optical gyrotron for plasma diagnostics is being developed in National Institute for Fusion Science in cooperation with Fukui University. The frequency tunabilities in two bands near 92 GHz (fundamental operation) and 184 GHz (second harmonic operations) will be achieved.
This paper summarizes achievements of 'Gyrotron FU series' and present status of the quasi-optical gyrotron development.

2. Gyrotron FU Series

Gyrotrons included in Gyrotron FU series are frequency step-tunable sources covering a wide wavelength range from millimeter to submillimeter wave region. The output powers are not so high, that is, from several hundreds watt to several tens kilowatt for fundamental operation and from several tens watt to several kilowatt for second harmonic operation. The main results are summarized as following.

(a) Frequency tunability in broad band from 38 GHz to 889 GHz[1-3]

All frequencies achieved up to now by 5 gyrotrons included in Gyrotron FU series are summarized as functions of field intensity B_0 in Fig. 1. Solid lines represent the fundamental ($f=f_c$), the second and the third harmonic ($f=2f_c$, $3f_c$) resonances. Frequency step-tunability from 38 to 889 GHz is achieved by the fundamental, second and third harmonic operations. Gyrotron FU IVA has achieved the highest frequency of 889 GHz for single mode operation on the $TE_{8,6,1}$ cavity mode at the second harmonic ($f=2f_c$). The corresponding wavelength is 337 μm.

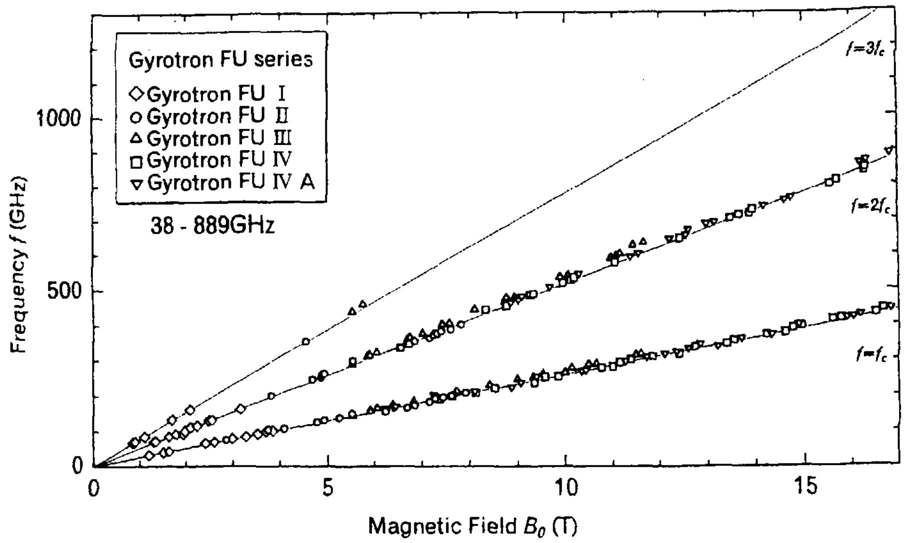

Fig.1 All frequencies achieved up to now by Gyrotron FU series as functions of field intensity B_0. Solid curves show the fundamental, the second harmonic and the third harmonic resonances.

(b) Amplitude modulation[4,5]

Gyrotrons FU III and IV have achieved amplitude modulation of their outputs. A modulation of the anode voltage V_a will modulate the velocity distribution function of beam electrons, which, in its turn, will modulate the gyrotron output. Fig. 2 shows a typical result of amplitude modulation in the submillimeter wave gyrotron (Gyrotron FU III) with the ratio $\Delta V_a / V_a$ as a parameter. This ratio represents the modulation level of the anode voltage V_a. The gyrotron, in this instance, is operating on the second harmonics of the cyclotron frequency. The cavity mode is $TE_{1,6,1}$, the frequency is 444 GHz, and the output power is about 300 W. The modulating frequency is 5 kHz and modulation mode is sinusoidal wave. The upper traces show the high voltage pulse applied to the anode. The small sinusoidal wave modulation signal is visible on the traces. The lower traces show the output power of the gyrotron. The modulation rate $\Delta P_{out}/P_{out}$ of gyrotron output increases with the modulation rate $\Delta V_a / V_a$ of the anode voltage. The 100 percent modulation of the output ($\Delta P_{out}/P_{out}$=1.0) is attained, when $\Delta V_a / V_a$ is only several percent ($\Delta V_a / V_a$~0.055). The modulation rate $\Delta P_{out}/P_{out}$ of output power is almost linearly proportional to $\Delta V_a / V_a$. This means the sinusoidal modulation of output power is possible by the sinusoidal modulation of anode voltage. Sinusoidal modulation of P_{out} at the modulation frequency up to 600 kHz has been achieved with the low $\Delta V_a / V_a$ value of $1.1 \cdot 10^{-3}$.

In Fig.3, the amplitude modulation efficiency $(\Delta P_{out}/P_{out})/(\Delta V_a/V_a)$ is plotted as a function of the beam current I_b. The theoretical prediction for the efficiency is derived from the energy transfer function between electrons and electromagnetic wave, as follows,

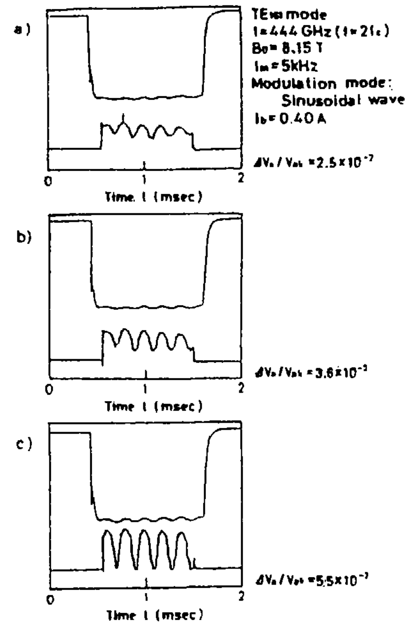

Fig. 2 Amplitude modulation result for Gyrotron FU III. Upper traces are high voltage pulses applied to the anode and lower traces output powers of gyrotron. Operation conditions are shown beside the figure. Unmodulated beam voltage V_b=40 kV.

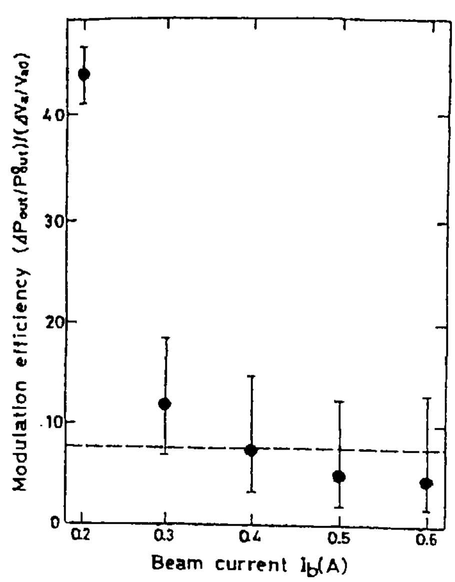

Fig. 3 Amplitude modulation efficiency of $(\Delta P_{out}/P_{out})/(\Delta V_a/V_a)$ as a function of the beam current I_b.

$$(\Delta P_{out}/P_{out})/(\Delta V_a/V_a) = (1 + P_{ohm}/P_{out})(3\alpha^2 + 4),$$

where P_{ohm} is the ohmic power loss in a cavity and α the pitch angle of beam electrons. The broken line in Fig.3 shows the efficiency when P_{ohm}/P_{out} is neglected. In the figure, experimentally obtained efficiency becomes close to the theoretical prediction (the broken line), when I_b is so high that P_{out} is high enough.

(c) Frequency modulation[6]

Gyrotron FU IV has achieved the frequency modulation within the limit of resonance frequency width of a cavity mode. The mechanism is as follows. The energy of beam electrons is modulated by variation in the body potential. The body includes the cavity and is separated electrically from the beam collector by a ceramic insulator. Therefore, the electron cyclotron frequency is modulated by the changing of electron mass and, as the results, a frequency modulation takes place.

The output power is transmitted by circular waveguides and emitted to a horn antenna. The frequencies measured by a heterodyne detection system consisting of a sweep oscillator, a frequency counter, a harmonic mixer and a modulation domain analyzer. The detected signal (f) is mixed with a high harmonic of the local oscillator and converted to the low frequency signal (f_{IF}). The time and frequency resolutions of the detection system are 10 μsec and 10 kHz, respectively.

A typical result of the frequency modulation experiment is demonstrated in Fig. 4. A trace in the left hand side shows the sinusoidal modulation of body potential V_b. The amplitude of the modulation is around 120 V. Corresponding frequency modulation is demonstrated in the f_{IF} trace in the right hand side. It is also close to sinusoidal modulation and the amplitude is around 30 MHz. The modulation frequency f_m is 10 kHz in this instance.

The frequency modulation amplitude Δf versus the body potential modulation amplitude ΔV_b is plotted in Fig. 5 for several values of the modulation frequency f_m. There is an almost linear dependence between Δf and ΔV_b for all values of f_m. The efficiency of frequency

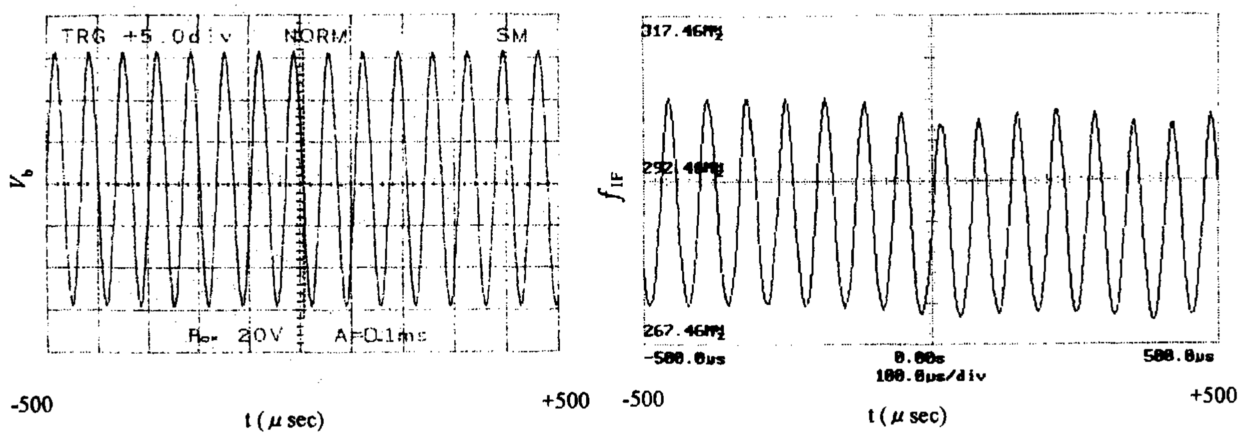

Fig. 4 Typical xperimental results of frequency modulation. The traces show the modulation ofV_b (in the left hand side) and the modulation of the output frequency which is demonstrated by the modulation of f_{IF} (in the right hand side) f_m=15 kHz, ΔV_b=120 V and Δf=31.1 MHz.

modulation $\Delta f / \Delta V_b$=0.247 MHz/V. The simulation results are also indicated by solid circles in the figure. The estimated efficiency is distributed close to the experimentally obtained values. The submillimeter wave gyrotron is used as a radiation source for plasma scattering measurement and ESR experiment in our laboratory. The advantages of frequency and amplitude modulations will be useful in these applications.

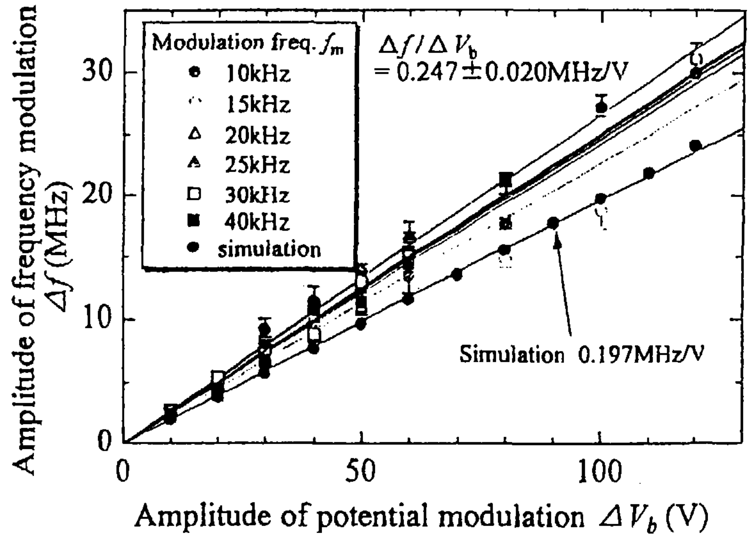

Fig. 5 Experimental and simulation results for frequency modulation amplitude Δf versus the amplitude of body potential modulation ΔV_b forf_m=10, 15, 20, 25, 30 and 40 kHz. Observed frequency modulation efficiency $\Delta f / \Delta V_b$=0.247 MHz/V. Output power P=20 W.

(d) Complete cw operation with high stabilities of amplitude and frequency

One of the advantages of complete cw operation is stabilization of the frequency and the amplitude of the gyrotron output. The longest period of the operation which our gyrotron series has achieved was 15 hours. This means 'complete cw'. We employ a current-stabilized high voltage power supply in our experiment to ensure stable operation. A variation in the output frequency was measured by a time-resolved frequency measurement system which is the same as the one used for measurement of frequency

modulation. The measured frequency variations δf during 100 msec are several MHz and $\delta f/f$ are of the order of 10^{-5} for several cavity modes. The output power variations measured by Schottky diode during ten minutes are several percent. These variations come from the variations of anode and cathode voltages of electron gun. We are planning first to stabilize both voltages, and then, we will try feed back control of them to achieve further high quality stabilization.
Fig.6 shows a preliminary result for amplitude stabilization by the feed-back control of the anode voltage of electron gun. It is seen in the upper trace, that the fluctuation level of the amplitude is decreased lower than 0.1 percent.

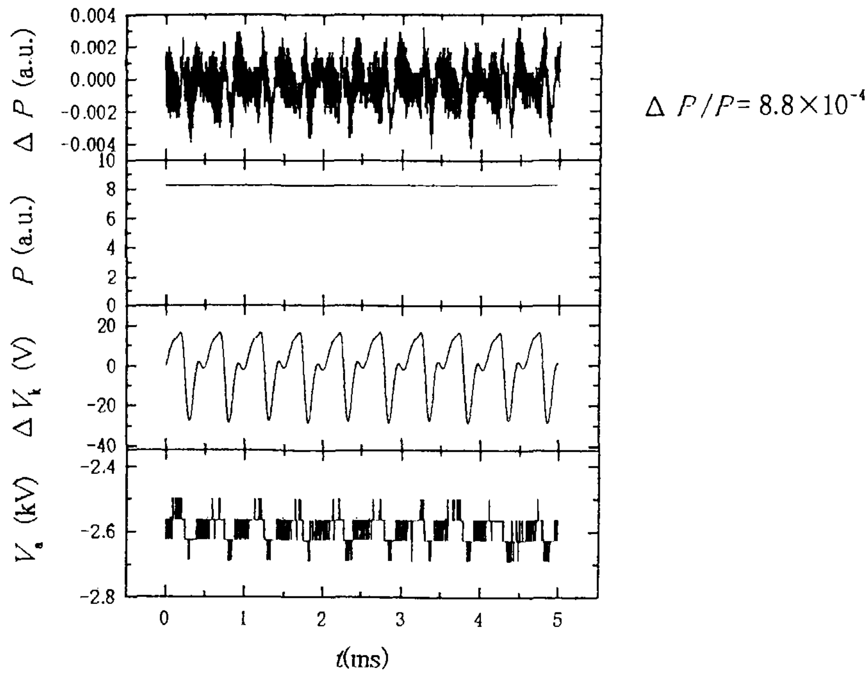

Fig. 6 A typical result of amplitude stabilization experiment by feed-back control of anode voltage V_a.

3. Quasi optical gyrotron

Fig. 7 shows a schematic drawing of a quasi optical gyrotron which is being developed by the collaboration between National Institute for Fusion Science and Fukui University. In the gyrotron, Fabry-Perot resonator is installed. It enables frequency tuning in wide ranges near 90 GHz and 180 GHz. The operation parameters of the gyrotron are listed inTable 1. The output powers obtained by computer simulations are around 100 kW for fundamental operations and 50 kW for second harmonic ones.

Table 1 The operation parameters of the quasi optical gyrotron

Frequency ranges	80~100 GHz (fundamental operations) 160~200 GHz (second harmonic operations)
Output power	~100 kW (fundamental operations) ~50 kW (second harmonic operations)
Efficiencies	20~30 % (fundamental operations) 10~20 % (second harmonic operations)
Maximum field	4.5 T
Electron beam parameter	70 kV, 10 A, 1msec (first stage) 80 kV, 20 A, 10 msec (final stage)

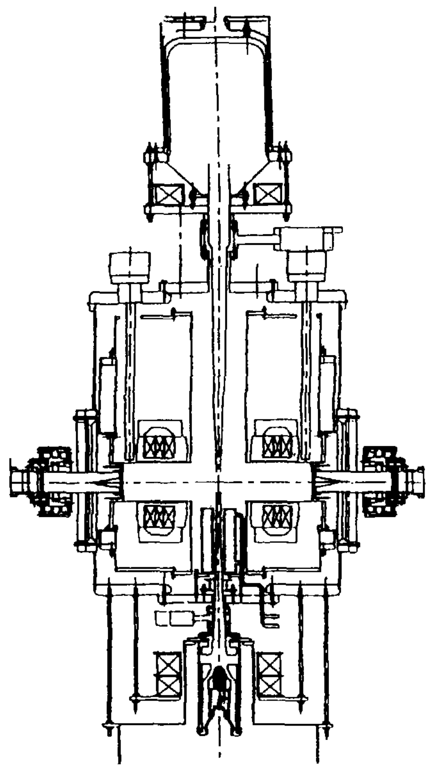

Fig. 7 A schematic drawing of the quasi optical gyrotron

Frequency tunability of such a high power gyrotron will be useful for application to plasma diagnostics and high power spectroscopies in wide fields.

4. Conclusion

We have developed frequency tunable, submillimeter wave gyrotrons (Gyrotron FU series) with medium power and a quasi optical millimeter wave gyrotron with high power for plasma diagnostics and millimeter to submillimeter wave spectroscopy. The former gyrotrons have achieved frequency and amplitude modulations and high stability of the output power.

The fluctuation level of output powers is now lower than 0.1 percent. These advantages of the gyrotron series enable us to apply them to high power, millimeter to submillimeter wave spectroscopies in wide fields. The gyrotrons are used for measurement of LHD in National Institute for Fusion Science in near future.

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