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High Quality Operation of a Submillimeter Wave Gyrotron for Plasma Diagnostics Application

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Abstract

The outputs (cw operation, f = 301 GHz, P ~ 20 W) of the Gyrotron FU IV are stabilized ($\Delta P/P$ ~ 1 %, Δf ~ 50 kHz) by decreasing the fluctuations of the potentials (ΔV_k ~ 0.6 V, ΔV_a ~ 0.2 V), via introducing smoothing circuits consisting of a resistor, an induction coil and a capacitor. Further stabilization of output frequency (Δf ~ 1 kHz) is attained by applying phase lock loop. Gyrotron FU VA can produce high mode purity outputs. The gyrotron has a nonlinear cavity which is designed using a scattering matrix code and exquisitely fabricated.

Keywords:

submillimeter wave gyrotron, high power source, stabilization, phase lock, high mode purity, radiation pattern

1. Introduction

Plasma scattering measurement is effective technique to observe low frequency density fluctuations (f < 1 MHz, k ~ 10 cm^{-1}) excited in plasma. The spatial and wave number resolutions and the S/N ratio of measurement depend on the wavelength range, the size and the intensity of a probe beam. A well-collimated, submillimeter wave beam to offer small scattering volume and relatively large scattering angle is suitable for improving the spatial and wave number resolutions. Up to now, molecular vapor lasers [1,2] and backward-wave oscillators [3,4] have been used as the principal power sources. However, their output powers are lower than 0.5 W and 10 mW, respectively.

Application of high frequency gyrotron is effective in improving the S/N ratio of the measurement because of their capacity to deliver high powers [5,6]. We have already carried out plasma scattering measurements using a high frequency gyrotron (Gyrotron FU II) [7]. It turns out that the stabilization of gyrotron output and high quality probe beam are required to improve the performance of the measurement.

In order to apply the gyrotron to plasma scattering measurement, we have stabilized the output (P = 20 W, f = 301 GHz) of gyrotron up to the level ($\Delta P/P$ < 1 %, Δf < 10 kHz) established by molecular vapor lasers. The gyrotron output can be stabilized by decreasing the fluctuations of the cathode potential and the anode potential. Because a gyrotron is characterized by voltage controlled oscillator [8], a high frequency stability can be attained by introducing phase lock loop.

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Unlike a molecular vapor laser, a gyrotron generates spreading radiation with TE_{mn} mode structure. It is therefore necessary to convert the output radiation into a Gaussian beam (TEM_{00} mode), which is suitable for an effective transmission and a well-collimated probe beam. High purity mode operation is convenient for effectively converting the output radiation into the Gaussian beam (TEM_{00} mode). We have constructed a new gyrotron, Gyrotron FU VA, which has a carefully designed resonant cavity developed in collaboration with the Max-Planck Institute for Plasma Physics and the Institute for High Power Pulse and Microwave Technology at the Research Center (FZK) Karlsruhe.

2. High Stabilization of the Gyrotron Output

We have achieved cw operation of the submillimeter wave gyrotron, Gyrotron FU IV. This gyrotron consists of sealed-off tube and magnet system. The superconducting magnet produces the main field in the cavity region whose intensity can be raised up to 12 T. Three subsidiary copper coils are used in the electron gun region. Both fields can be adjusted independently to control the formation of the electron beam produced by the Magnetron Injection Gun (MIG). The cw operation (TE_{03} mode, f = 301 GHz, P = 20 W) is obtained under the following conditions: magnetic field intensity in the cavity region B_0 = 10.8 T, cathode potential V_k = −16 kV, anode potential V_a = −2.9 kV. The output power of cw operation was not stable (~ 5 %) due to the fluctuation of the cathode potential (ΔV_k ~ 40 V). The evolution of operation parameters with time is shown in Fig. 1. The fluctuation of the output power correlates with that of the cathode potential ΔV_k. When ΔV_k decreases to the minimum value, $\Delta P/P$ reaches its maximum as shown in Fig. 1. In order to suppress the fluctuation level of the cathode potential and the anode potential, high voltage power supplies are equipped with smoothing circuits consisting of a resistor, an induction coil and a capacitor (Fig. 2). The fluctuation level was decreased (ΔV_k ~ 0.6 V, ΔV_a ~ 0.2 V) by introducing the smoothing circuit. Accordingly, the fluctuations of the output power were decreased from 4 % to 1 %.

A gyrotron functions as a voltage controlled oscillator. This enables us to attain a high stability of output frequency by introducing a phase lock loop. Compared to conventional sources (gunn oscillator, BWO), a gyrotron has small frequency modulation sensitivity. The value of the gyrotron FU IV obtained by changing the potential of body electrode is 0.016 MHz/V. In order to compensate the mismatch of modulation sensitivity, we introduce an amplifier between a phase lock module for gunn oscillator and a control electrode (Fig. 3). The phase lock signal is fed back to the body electrode of the gyrotron across a load resister of 1 kΩ. The body electrode is connected with cavity region and its potential is close to grounding potential. Frequency

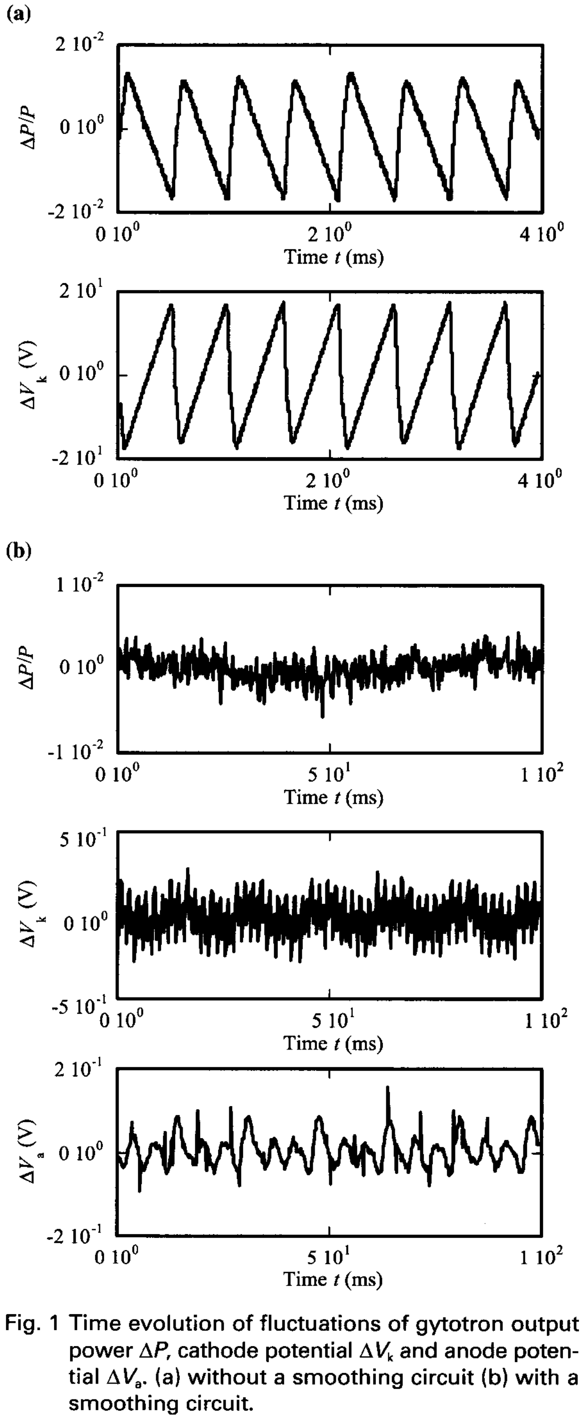

Fig. 1 Time evolution of fluctuations of gytotron output power ΔP, cathode potential ΔV_k and anode potential ΔV_a. (a) without a smoothing circuit (b) with a smoothing circuit.

stabilization is effectively improved by introducing phase lock loop from $\Delta f \sim 50$ kHz to $\Delta f \sim 1$ kHz (Fig. 4).

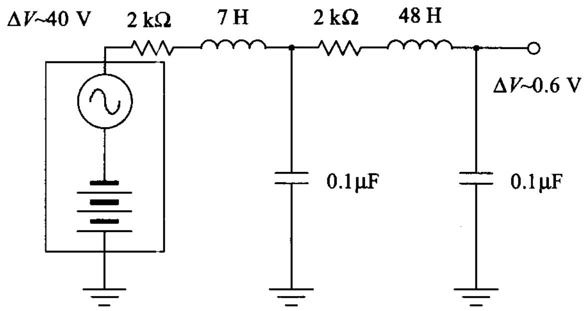

Fig. 2 A smoothing circuit to suppress output voltage fluctuations.

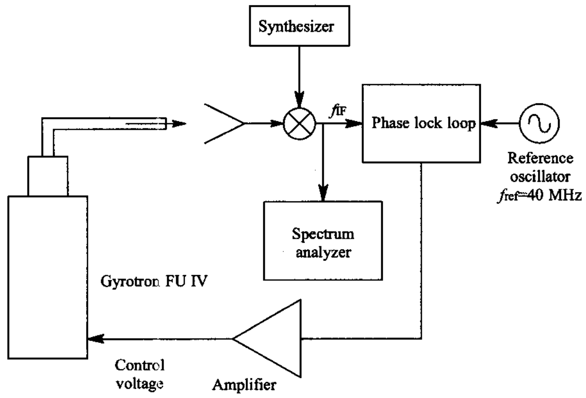

Fig. 3 Block diagram of a phase lock system.

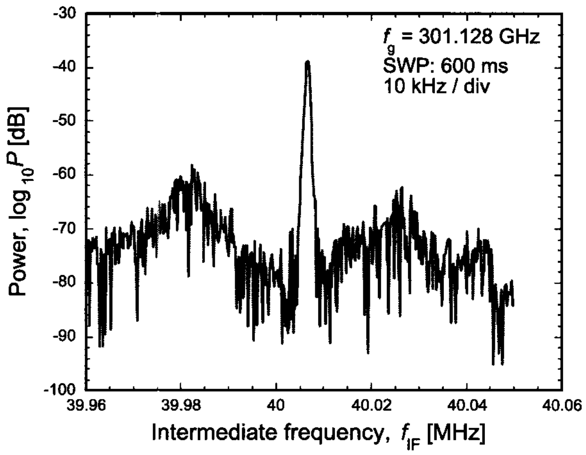

Fig. 4 A logarithmic plot of frequency spectrum of intermediate frequency signal under phase-locked stabilization.

3. High Purity Mode Operation of a Gyrotron

Gyrotron FU VA (Fig. 5) is constructed using a helium-free superconducting magnet. This magnet can produce a magnetic field up to 8 T without using liquid helium. The tube is demountable, because we will try to optimize all components, the cavity, the transmission waveguide and the output window. The window is made by quartz plate with the thickness of 3.175 mm and relative dielectric constant of 3.83.

In order to avoid conversion of the cavity mode to spurious modes, the cavity (Fig. 6) has an optimized design with nonlinear up-tapers and a rounded iris at the output. The resonance calculation using a scattering matrix formalism (SM-code) was performed taking into account the complete gyrotron geometry including the pumping sections (slots) and the window [9]. Table 1 shows output mode purities and quality factors for different modes.

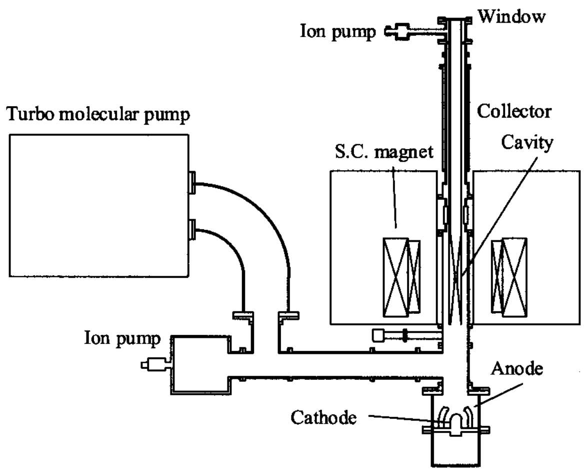

Fig. 5 A schematic drawing of Gyrotron FU VA.

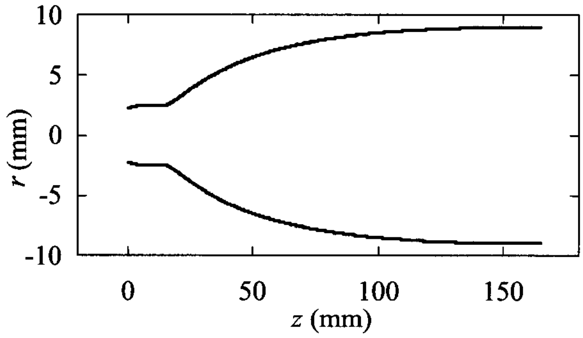

Fig. 6 The shape of the cavity installed in Gyrotron FU VA.

Table 1 Calculated resonance frequencies f_{res}, diffractive quality factors Q_D and output mode purities η for the complete Gyrotron FU VA.

mode	f_{res} (GHz)	Q_D	η (%)
TE_{01}	73.85	251	97.99
TE_{12}	102.36	1020	98.54
TE_{02}	134.40	2910	97.26
TE_{13}	163.37	3109	99.42
TE_{03}	194.57	2603	99.02
TE_{04}	254.63	11569	98.49
TE_{16}	344.13	27712	87.65
TE_{06}	374.65	101064	93.83

The radiation patterns are measured by two-dimensionally (x-y plane) moving pyro-electric detector array over the gyrotron window. The intensity profiles of radiation pattern for TE_{32}-, TE_{03}- and TE_{13}-mode are shown in Fig. 7. These patterns are not so affected by the diffraction at the output aperture of waveguide because they are measured in the far-field region ($z > z_f = ka_w^2 \sim 200$ mm).

The patterns for these modes agree well with the intensity profiles calculated. This demonstrates that Gyrotron FU V can produce outputs of high purity mode. As can be seen from Figs. 7(a) and (c), this gyrotron does not produce a rotating mode but a non-rotating mode. Such a feature is favorable for converting gyrotron output into a Gaussian beam, because a quasi-optical antenna is available for a set of TE_{0n} mode outputs and non-rotating TE_{1n} mode outputs.

4. Conclusions

The output of the Gyrotron FU IV (f = 301 GHz, P ~ 20 W) obtained by cw operation is stabilized up to 1 % and 50 kHz by decreasing the fluctuations of the potentials ($\Delta V_k \sim 0.6$ V, $\Delta V_a \sim 0.2$ V), via introducing a smoothing circuit consisting of a resistor, an induction coil and a capacitor. As a result of phase lock loop, we succeeded to reduce the frequency fluctuation within 1 kHz.

To produce high purity mode outputs, a carefully designed cavity is installed in Gyrotron FU VA. The measurement of radiation patterns demonstrates high purity non-rotating mode operations. The resonance calculation for a complete gyrotron geometry using scattering matrix formalism (SM-code) was carried out and the results were compared with the measurement.

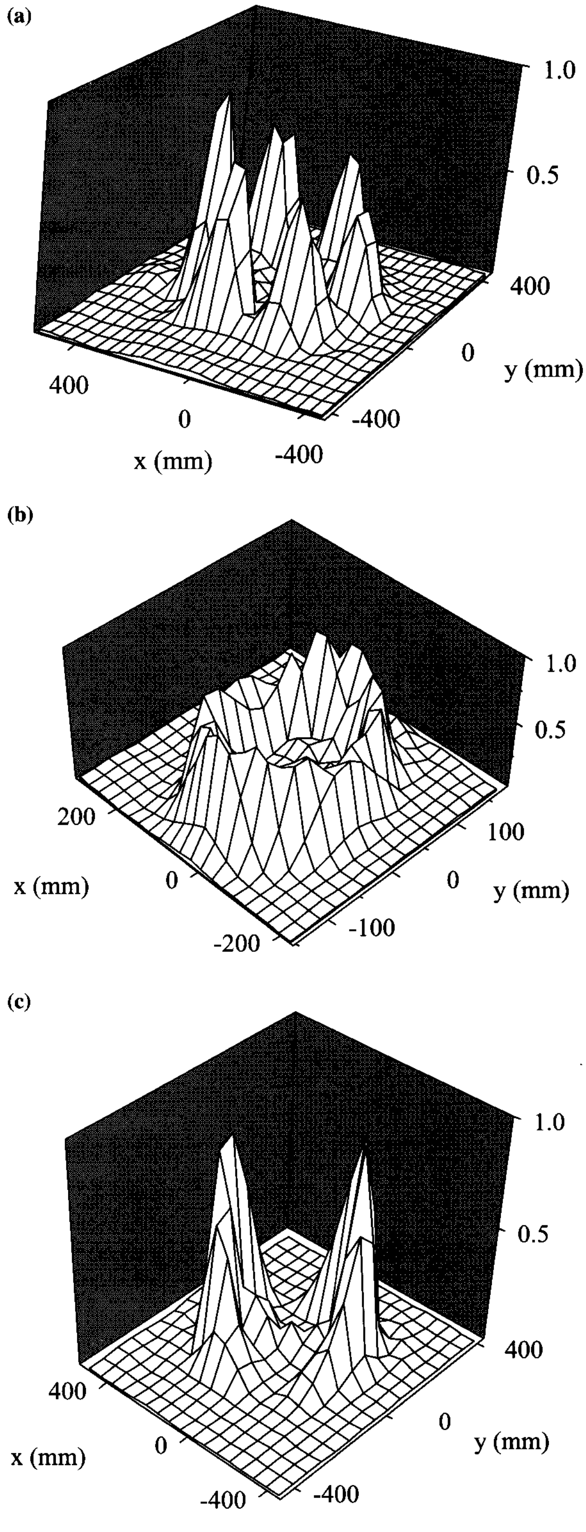

Fig. 7 Intensity profiles of radiation pattern. (a) intensity profile for TE_{32} mode (B_0=5.5 T, f=151 GHz, z=730 mm), (b) intensity profile for TE_{03} mode (B_0=7.0 T, f=194 GHz, z=350 mm), (c) intensity profile for TE_{13} mode (B_0=5.8 T, f=163 GHz, z=730 mm).

Acknowledgments

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