Development of Frequency Tunable, Medium Power Gyrotrons (Gyrotron FU Series) as Submillimeter Wave Radiation Sources

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journal or publication title	IEEE Transactions on Plasma Science
volume	PS-27
number	2
page range	340-354
year	1999-04
URL	http://hdl.handle.net/10098/1510

Development of Frequency Tunable, Medium Power Gyrotrons (Gyrotron FU Series) as Submillimeter Wave Radiation Sources

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(Invited Review)

Abstract—High frequency, medium power gyrotrons (Gyrotron FU series) have been developed at Fukui University as radiation sources covering a broadband from millimeter to submillimeter wave region. They have already been applied to high frequency electron spin resonance and to submillimeter wave scattering in plasma. Many parameters of the gyrotron series could be useful for its applications in several new areas. The development and some applications of the Gyrotron FU series are summarized in this paper.

Index Terms—Gyrotron, submillimeter wave.

I. 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, electron cyclotron current drive of tokamaks [1]–[5], and for ceramic sintering [6], [7]. At present, 120–170 GHz, 1 MW, pulse gyrotrons are designed for plasma heating, and a 30 GHz, 15 kW, CW gyrotron for ceramic sintering.

The second direction is the development of high frequency, medium power gyrotrons [8], [9] as millimeter to submillimeter wave sources for plasma scattering measurements, [10], [11], electron spin resonance (ESR) experiments [12], and so on. Such gyrotrons operate on fundamentals, second, and even third harmonics of the electron cyclotron resonance under high magnetic field exceeding 10 T. They have many advantages over other conventional sources, like frequency tunability and high power output.

Gyrotrons developed at Fukui University belong to the second group. They are high frequency, medium power gyrotrons covering a broad frequency band from millimeter to submillimeter wavelength region. Our “Gyrotron FU series” consists of eight gyrotrons. The latest gyrotron of the series, Gyrotron FU IVA [13] has achieved frequency tunability

from 160 to 889 GHz with many single mode operations on fundamentals and on second harmonics of electron cyclotron frequency. This gyrotron is employed in high purity mode operation experiments. Its maximum frequency of 889 GHz is the current record for high frequency operation of a gyrotron. The corresponding wavelength is 337 μm . This gyrotron is also applied as a radiation source in high frequency ESR experiments.

The previous gyrotron, Gyrotron FU IV [14], has also achieved frequency tunability up to 847 GHz. It was successfully employed in first experiments with frequency modulation [15] as well as for CW operation with high stability of amplitude and frequency [16].

Gyrotron FU III [17] achieved frequency tunability up to 636 GHz operating on fundamentals, on second harmonics, and even on third harmonics. The gyrotron demonstrated amplitude modulation [18] and frequency step switching [19] of its output. It is useful for its applications as radiation source in infrared spectroscopy.

Gyrotron FU II [20] is the first submillimeter wave gyrotron in the series. Its maximum frequency is 402 GHz. It has been used for plasma scattering measurements on compact helical system (CHS) at the National Institute for Fusion Science (NIFS) in Japan. Its output power of about 100 W at 352 GHz is transmitted by a circular waveguide system. It is later converted into a quasi-Gaussian mode and injected into the CHS plasma. A scattered signal is analyzed by a homodyne detection system. The measurement confirmed the excitation of a low frequency drift wave during neutral beam injection (NBI) heating. Such information is important to achieve the best plasma confinement. We intend to apply this gyrotron for plasma diagnostics on experimento tokamak esferico (ETE) at Instituto Nacional de Pesquisas Espaciais (INPE) in Brazil. The gyrotron was also used for studies of mode competition [21] and mode cooperation [22]. These studies give some insights for high efficient, single mode operations on second harmonics. The first gyrotron, Gyrotron FU I [23] is frequency tunable from 38–220 GHz. It has been used as a radiation source for ESR experiment. Gyrotron FU IA has been applied as a radiation source for millimeter wave scattering measurement of WT-3 at Kyoto University [24].

Now we have constructed a new gyrotron, Gyrotron FU V [25] using a helium-free, 8 T superconducting magnet. The tube is demountable, because we will try to optimize all

Manuscript received July 20, 1998; revised January 19, 1999. This work was supported in part by a Grant-in-Aid from the Ministry of Education, Science, and Culture (Monbusho) of Japan, the International Joint Research Project from the Japan Society for the Promotion of Science, and the German–Japan Scientific Research Program from Deutsche Forschungsgemeinschaft (DFG) in Germany.

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Publisher Item Identifier S 0093-3813(99)04857-2.

TABLE I
PRESENT STATUS OF GYROTRON FU SERIES

Name of gyrotron	Frequency range	Items which each gyrotron has achieved
Gyrotron FU I	38-220 GHz	Radiation source for ESR experiment
Gyrotron FU E	90-300 GHz	Radiation source for ESR experiment
Gyrotron FU IA	38-215 GHz	Radiation source for plasma scattering measurement of WT-3 Studies on mode competition and mode cooperation
Gyrotron FU II	70-402 GHz	Radiation source for plasma scattering measurement of CHS
Gyrotron FU III	100-636 GHz	3rd harmonic operation in single modes, Amplitude modulation, Frequency step switching
Gyrotron FU IV	160-847 GHz	Frequency modulation, cw operation for high stabilities of amplitude and frequency
Gyrotron FU IVA	160-889 GHz	Higher frequency operations by 3rd harmonics, High purity mode operation, Radiation source for ESR experiment

Fig. 1. The shape of a cylindrical cavity installed in Gyrotron FU IV.

components including the cavity, the transmission waveguide, the window, and so on. Our aim is to realize high mode purity operations. The gyrotron has the other advantage, namely, a long run in complete CW operation, because it is not restricted by the supply of liquid helium. After testing of its operation quality, the gyrotron will be applied for research in material physics, in plasma scattering phenomena, and so on.

The parameters achieved by Gyrotron FU series are summarized in this paper.

II. DEVELOPMENT OF GYROTRON FU SERIES

A. Designs and Constructions of High Frequency, Harmonic Gyrotrons

1) *The Present Status of Gyrotron FU Series:* Gyrotron FU series includes eight gyrotrons. Each gyrotron consists of a sealed-off gyrotron tube and a superconducting magnet, except Gyrotron FU III, which has a demountable tube. Table I summarizes the present status of gyrotrons included in Gyrotron FU series.

The design was carried out by computer simulations. We are using narrow cavities to get a good mode separation, and then to operate the gyrotrons in many single modes on fundamentals, second, even third harmonics. Such operation is important for our high frequency, harmonic gyrotrons. For

example, the diameter of the previous gyrotron, Gyrotron, FU IV [14] is only 3.23 mm, as is shown in Fig. 1. Beam currents sustaining 100 W output power are plotted in Fig. 2 for many cavity modes as functions of the magnetic field intensity B_0 . The parameter ($N = f/f_c$, f , and f_c are the operating frequency and the electron cyclotron frequency) indicates the harmonic number. A 17 T superconducting magnet is used for Gyrotron FU IV. As it is obvious from the figure, there are many candidates for single mode operation on fundamentals ($N = 1$), second harmonics ($N = 2$), and even on third harmonics ($N = 3$) in the region of field intensity from 14.5 to 17 T. If we adjust field intensity B_0 to its optimal value, we can operate some of second harmonics in Fig. 2, suppressing mode competition with any fundamentals of higher output power. We can expect that the maximal frequency of the second harmonic is about 850 GHz for single mode operation at $TE_{4,8,1}$ cavity mode. The other gyrotrons in Gyrotron FU series are designed along the same lines as Gyrotron FU IV.

2) *Gyrotron FU IVA:* A schematic drawing of the latest gyrotron, Gyrotron FU IVA [13], is shown in Fig. 3. The gyrotron consists of a 17 T superconducting magnet and a sealed-off tube. A triode magnetron injection gun operates in the magnetic field leaking from the superconducting magnet. The mirror ratio, that is, the ratio of the main field intensity at the cavity region to the intensity at the cathode of the electron gun, is about 45. Fig. 4 shows a computer simulation

Fig. 2. Computer simulation results for beam currents I_b sustaining 100 W output power for several cavity modes as functions of magnetic field intensity B_0 . The parameter N shows harmonic number.

result for anode voltage V_a of the gun keeping the velocity ratio α at 1.5 ($\alpha = v_1/v_2$, v_1 , and v_2 are the perpendicular and parallel velocity components, respectively), as a function of field intensity B_0 . Solid circles and open circles present results for Gyrotrons FU IVA and IV, respectively. The solid circle encircled by an open circle corresponds to the second harmonic operation on $TE_{1,9,1}$ cavity mode with frequency of 874 GHz. As it follows from this figure, we can control the pitch factor α in the broad range of field intensity from 5 to 17 T, adjusting only the anode voltage V_a . The cavity with the diameter of 3 mm and the length of 6.25 mm only is installed in the gyrotron. The shape of the cavity is shown in Fig. 5. It contains a nonlinear up taper in the output region and smooth junctions to the cutoff down taper and to the output up taper to minimize mode conversion from the main cavity mode to competing modes. The cavity also has a small iris at the output end to increase its quality factor, and hence to decrease the starting current for working cavity modes. The design of this cavity was carried out very accurately by Wagner from Stuttgart University and Thumm from Forschungszentrum Karlsruhe [26]. Computer simulation results for conversion from the main cavity mode $TE_{2,6,1}$ to its competing modes ($TE_{2,5,1}$, $TE_{2,7,1}$, and so on) in the nonlinear up taper are shown in Fig. 6. A part of the main mode is converted to

the $TE_{2,5,1}$ and $TE_{2,7,1}$ modes in the middle of the up-taper region, but almost all power returns back to the main mode at the end of the up taper. Calculation results predict that 99.3% of total power can be transmitted through the up-taper region. Fig. 7 presents simulation results with equi-oscillation-efficiency lines for third harmonic operation ($N = 3$) on the $TE_{2,10,1}$ and $TE_{9,7,1}$ modes, together with fundamental operation ($N = 1$) on the $TE_{9,1,1}$ mode. The vertical and horizontal axes correspond to the injection point of electron beam in the cavity and field intensity B_0 , respectively. The injection region of electrons in our device is shown. Single mode operation on third harmonic ($N = 3$) is possible only by adjusting field intensity B_0 to optimal conditions. The frequencies of $TE_{2,10,1}$ and $TE_{9,7,1}$ modes are 1022 and 1034 GHz. Therefore, we expect this gyrotron can achieve the breakthrough of 1 THz.

B. Experimental Results for High Frequency, Harmonic Gyrotrons (Gyrotron FU Series)

As it is shown in Table I, 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

Fig. 3. A schematic drawing of Gyrotron FU IV A.

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 achieved up to now by Gyrotron FU series are summarized as following.

1) *Frequency Tunability in Broadband from 38–889 GHz* [13], [14], [17], [20], [21]: Seven gyrotrons in the series have achieved frequency step tunability in the ranges shown in Table I. Fig. 8 shows a typical result of frequency measurement for Gyrotron FU IV using a Fabry–Perot interferometer. There are many instances of single mode operation on fundamentals [Fig. 8(a)] and on second harmonics [Fig. 8(b)]. Each interferometer pattern corresponds to field intensity B_0 indicated by an arrow. The measured wavelengths, their corresponding frequencies, and the cavity modes are shown in the figure. All frequencies achieved up to now by Gyrotron FU series are summarized as functions of field intensity B_0 in Fig. 9. Solid lines represent the fundamental ($N = 1$),

Fig. 4. Computer simulation results for anode voltage V_a of electron gun keeping the velocity ratio α at 1.5 as functions of field intensity B_0 . • and ○ correspond to Gyrotrons FU IVA and FU IV.

the second, and the third harmonic ($N = 2, 3$) resonances. Frequency step tunability from 38 to 889 GHz is achieved for the fundamental, second, and third harmonic operation. Gyrotron FU IVA achieved the highest frequency of 889 GHz for single mode operation on the $TE_{8,6,1}$ cavity mode at the second harmonic ($N = 2$). The corresponding wavelength is 337 μm . Table II is a list of all frequencies achieved by Gyrotron FU IV, together with corresponding field intensities, cavity modes, and several output powers measured by a water load. In the case of Gyrotron FU IV, output powers are several hundreds watt at fundamentals and several tens watt at second harmonics. Similar frequency tunability has been achieved by each gyrotron of the series, as it is shown in Table I and in Fig. 9. The Gyrotron FU series covers a broad frequency band from millimeter to submillimeter wave region (38–889 GHz).

2) *Amplitude Modulation* [18], [27]: An amplitude modulation and frequency modulation of submillimeter wave gyrotrons are useful for their applications in various new areas as radiation sources. Gyrotron FU III has achieved amplitude modulation of its output. 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. 10 shows a typical result of amplitude modulation in the submillimeter wave gyrotron, with the modulation level of anode voltage V_a expressed as the ratio $\Delta V_a/V_{a0}$ as a parameter. The gyrotron, in this instance, is operating on the fundamental of the cyclotron frequency. The cavity mode is $TE_{6,2,1}$, the frequency is 349 GHz, and the output power is about 60 W. The modulating frequency is 5 kHz and modulation mode is square wave. The upper traces show the high voltage pulse applied to the anode. The small square wave modulation signal is visible on the traces. The lower traces show the output power of the gyrotron. The modulation rate $\Delta P_{\text{out}}/P_{\text{out}}$ of gyrotron output increases with the modulation rate $\Delta V_a/V_a$ of the anode voltage. The 100% modulation of the output ($\Delta P_{\text{out}}/P_{\text{out}} = 1.0$) is attained, when $\Delta V_a/V_a$ is only several percent ($\Delta V_a/V_a \sim 0.076$). Fig. 11 shows the modulation rate $\Delta P_{\text{out}}/P_{\text{out}}$ of output power as functions

Fig. 5. The shape of the cavity installed in Gyrotron FU IVA.

Fig. 6. Computer simulation result for mode conversions from the main cavity mode $TE_{2,6,1}$ to its competing modes $TE_{2,5,1}$, $TE_{2,7,1}$, and so on, occurring in the nonlinear up-taper region.

of the modulation rate $\Delta V_a/V_{a0}$, with the beam current as a parameter. $\Delta P_{out}/P_{out}$ is linearly proportional to $\Delta V_a/V_{a0}$. 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 $\Delta V_a/V_{a0}$ value of 1.1×10^{-3} .

3) *High Purity Mode Operations* [13]: Gyrotron FU IVA is designed for high purity mode operations as described in the previous section. Carefully designed cavity, possessing a nonlinear up taper in the output side and smoothly connecting parts in the beginning of the cutoff taper and the nonlinear up taper, is installed. Such structure of the cavity will minimize the mode conversions from the main cavity mode to its competing modes [26].

The propagation angle of each mode in a cylindrical waveguide has its own value. (A different mode has a different angle.) We set a step-cut waveguide on the top of the gyrotron tube as shown in Fig. 12 and measured the angle dependency of emitted power by using a Vlasov type antenna. This measurement determines the power distribution for each mode.

Fig. 7. Computer simulation result with equi-oscillation-efficiency lines for third harmonic operation on $TE_{2,10,1}$ and $TE_{9,7,1}$ modes, together with fundamental operation on $TE_{9,1,1}$ mode.

Table III summarizes the results for the main cavity mode TE_{031} , whose resonant frequency is 323.8 GHz. In this case, a Fabry-Perot interferometer pattern shows the operation is single mode at the fundamental cyclotron resonance. The observed frequency determined from the interferometer pattern is 323 GHz, which is close to calculated value. Operation conditions are as follows: the acceleration voltage of electron beam $V_b = 35$ kV, the electron beam current $I_b = 0.85$ A, and the field intensity in the cavity region $B_0 = 11.97$ T. In the measurement, 82% of the total power is emitted as the main cavity mode TE_{031} .

In the table, calculation results for the complete tube [26] are also indicated on the right-hand side column. It shows that about 89.6% of the total power can penetrate from the cavity to the output window. Agreement between experimental and calculation results is fairly good. In Gyrotron FU IVA, the design of the cavity is complete, but the other part is not optimized. So, the total mode purity, which determines the mode purity of the output power, was degraded by ten or twenty percent.

4) *Complete CW Operation with High Stability of Amplitude and Frequency* [16]: Fig. 13 shows the variations of tempera-

Fig. 8. A typical result of frequency measurement for Gyrotron FU IV using a Fabry-Perot interferometer. Interferometer patterns for: (a) the fundamentals and (b) the second harmonics.

Fig. 9. 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.

ture of the water in the water load measured for several cavity modes by a thermocoupler as functions of time. The slope of each observed line is proportional to the corresponding output power. The results of power estimations are following: 4.5 W for TE₀₂₁ mode at the frequency of 207.5 GHz, 20.1 W for TE₃₂₁ mode at 238.3 GHz, and 17.1 W for TE₀₃₁ mode at 301.9 GHz. The longest period of the operation was five hours, which means "complete CW."

Similar measurements have been made for many other cavity modes. Table IV summarizes the results, together with field intensity in the cavity region B_0 , accelerating voltage of elec-

tron beam V_b , beam current I_b , cavity mode TE_{*m**n*1}, frequency f measured by the Fabry-Perot interferometer and/or the modulation domain analyzer, input power P_{in} , and operation efficiency η .

The electron beam current I_b is several tens of milliamperes. It was limited by the water cooling capacity. It is close to the starting currents of corresponding cavity modes. Therefore, operation is not so stable, but the powers obtained are moderately high and the efficiency η exceeds 1% for a few modes.

One of the advantages of complete CW operation is stabilization of the frequency and the amplitude of the gyrotron

TABLE II
LIST OF ALL FREQUENCIES OBSERVED FOR GYROTRON FU IV, TOGETHER WITH CORRESPONDING
FIELD INTENSITIES, CAVITY MODES, AND SEVERAL OUTPUT POWERS MEASURED BY A WATER LOAD

B_0 (T)	$f = f_c$ (GHz)	$f = 2f_c$ (GHz)	P (W)	TE $m \ n$	B_0 (T)	$f = f_c$ (GHz)	$f = 2f_c$ (GHz)	P (W)	TE $m \ n$
6.23	159			1 2	11.85	309			5 2
6.55		336		3 3	12.42	316			9 1
6.73		346		1 4	12.44		647		6 5
7.31		376		4 3	12.74	337		107	3 3
7.38	190			5 1	13.40	346			1 4
7.64	199		403	2 2	13.49		703		5 6
8.13	208			0 2	13.55	356		55	6 2
8.34		443		3 4	13.68		714		3 7
8.52	221			6 1	13.90		718	51	1 8
8.77		455		9 2	13.96		729		8 5
9.27		486		0 5	14.25	372		107	4 3
9.34		489		7 3	14.63	378			11 1
9.35	237		456	3 2	14.79	390			2 4
9.58	253			1 3	14.97	396			0 4
9.86	255			7 1	15.57		802		3 8
9.97		521		11 2	15.62	414			5 3
10.14		529		3 5	15.71		812	63	1 9
10.20		536		1 6	15.80	417			8 2
10.76	278		253	4 2	16.30		838		6 7
11.00	281			8 1	16.32		847		4 8
11.05		577		2 6	16.52	431			3 4
11.15	293			2 3	16.67	443			1 5
11.38	301			0 3

Fig. 10. Amplitude modulation result for Gyrotron FU III. Upper traces are high voltage pulses applied to the anode and lower traces output powers of the gyrotron. Operation conditions: TE_{6,2,1} mode at the fundamental, modulation frequency is 5 kHz, and modulation mode is square wave, the frequency $f = 349$ GHz, unmodulated beam voltage $V_b = 40$ kV, and beam current $I_b = 0.3$ A.

output. 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.

Fig. 14 shows a typical result of frequency measurement, together with the accelerating voltage V_b . The operation con-

ditions are following: the field intensity in the cavity region $B_0 = 10.88$ T, the accelerating voltage of electron beam $V_b = 14$ kV, the beam current $I_b = 80$ mA, the cavity mode TE₀₃₁, the frequency $f = 301.9$ GHz, the input power $P_{in} = 1.12$ kW, the output power $P_{out} = 17.1$ W, and the operation efficiency $\eta = 1.53\%$. The measured frequency

 Fig. 11. Modulation level of the output power $\Delta P_{out}/P_{out}$ as functions of modulation level $\Delta V_a/V_a$, with beam current I_b as a parameter.

Fig. 12. The arrangement of a step-cut waveguide on the top of the gyrotron and quasi-optical Vlasov antenna for measurement of content ratio of each mode.

 TABLE III
EXPERIMENTAL AND SIMULATION RESULTS FOR RATIO OF EACH
OUTPUT MODE, WHEN THE CAVITY OPERATES ON TE₀₃₁ MODE

Cavity mode	Radiation angle α (Degree)	Detected power I_b (mA)	Mode purity (%) Experimental	Mode purity (%) Calculated
0 1	3.23	0.00	0	0.02807
0 2	5.93	0.30	1	1.59109
0 3	8.62	38.41	82	89.58727
0 4	11.33	6.62	14	2.28597
0 5	14.05	1.32	3	0.02247
0 6	16.81	0.00	0	0.00648

variation δf during 100 ms is $\delta f = 4.1$ MHz. The variation ratio $\delta f/f = 1.3 \times 10^{-5}$. The frequency variation is increased, probably due to a variation in the accelerating voltage V_b . The variation amplitude of V_b in the figure is about 10 V. It causes a small variation in the electron mass, and from it we can estimate the variation in the electron cyclotron frequency δf_c as 5.6 MHz. Its variation ratio $\delta f_c/f_c = 1.9 \times 10^{-5}$. The experimentally obtained values of $\delta f/f$ are in good agreement with the estimated value of $\delta f_c/f_c$.

Similar measurements have been carried out for several other modes. The results are summarized in Table V. In the

Fig. 13. The results of power measurements using a water load.

 Fig. 14. (a) A result of frequency measurement. A full scale in the vertical axis is 50 MHz and (b) a simultaneous observation result of acceleration voltage V_b . 10 V/div in the vertical axis.

table, the frequency variation δf during 100 ms is listed for several cavity modes, together with the cavity mode TE_{mnl}, the frequency of the local oscillator f_L , the harmonic number of the mixer n , the frequency f_{IF} detected by the modulation domain analyzer, and the determined operation frequency f , as well as calculated resonant frequency of the cavity. For all cases, δf is several MHz and $\delta f/f$ is of the order of 10^{-5} .

The stability of the operation frequency may be improved by further stabilization of the output voltage of a high voltage power supply.

TABLE IV
THE RESULTS OF MEASUREMENTS OF OUTPUT POWER P_{out} , TOGETHER WITH FIELD INTENSITY IN THE CAVITY REGION B_0 , ACCELERATION VOLTAGE OF ELECTRON BEAM V_b , BEAM CURRENT I_b , CAVITY MODE TE_{mn} , FREQUENCY f MEASURED BY A FABRY-PEROT INTERFEROMETER AND/OR A HETERODYNE DETECTION SYSTEM, INPUT POWER P_{in} , AND OPERATION EFFICIENCY η

B_0 (T)	V_b (kV)	I_b (mA)	TE_{mn}	f (GHz)	P_{in} (W)	P_{out} (W)	η (%)
7.09	12	64	2 2	199.3	768		
7.53	12	32	0 2	207.5	384	4.5	1.2
7.95	14	32	6 1	221	448	2.0	0.45
8.52	14	68	3 2	238.3	952	20.1	2.1
9.06	14	75	1 3	252	1050	9.8	0.93
9.14	14	67	7 1	253.6	938	3.2	0.34
10.53	15	80	2 3	295	1200	11.6	0.97
10.88	14	80	0 3	301.9	1120	17.1	1.53

Fig. 15. Schematic drawing of installation of scattering measurement system using Gyrotron FU II on CHS.

Fig. 16. Time evolution of frequency spectrum of scattered signal. Time intervals of ECH and NBI pulses are indicated.

TABLE V
THE FREQUENCY VARIATION δf DURING 100 ms IS LISTED FOR SEVERAL CAVITY MODES, TOGETHER WITH CAVITY MODE TE_{mn1} , FREQUENCY OF LOCAL OSCILLATOR f_L , HARMONIC NUMBER OF THE MIXER n , FREQUENCY f_F DETECTED BY THE MODULATION DOMAIN ANALYZER, DETERMINED OPERATION FREQUENCY f , AND CALCULATED RESONANT FREQUENCY f_{cal} OF THE CAVITY

Mode	Local Oscillator f_L (GHz)	Harmonic Number n	Modulation Domain Analyzer f_F (MHz)	f meas. (GHz)	δf (MHz)	f_{cal} (GHz)
TE_{11}	16.572	12	429	199.293	3.4	198.395
TE_{11}	12.227	17	342	207.517	4.4	207.526
TE_{11}	13.246	18	168	238.260	2.6	237.027
TE_{11}	10.548	24	483	253.630	5.2	253.634

III. APPLICATION OF GYROTRON FU SERIES

A. Application to Plasma Scattering Measurement

As it is shown in Table I, Gyrotron FU II is employed as a radiation source for plasma scattering measurements on the compact helical system (CHS) of the National Institute for Fusion Science (NIFS). A gyrotron is a well-suited source for plasma scattering measurement, because of its high power possibilities in submillimeter wave range. Gyrotron FU II delivers long pulses (pulse width is changed up to 0.6 s) of moderately high power (~ 110 W) at submillimeter wavelengths ($f \sim 354$ GHz, $\lambda = 0.847$ mm) [10]. Its application enables us to improve the S/N ratio of a measurement and to observe low level density fluctuations.

Fig. 15 shows the installation of a scattering measurement system on CHS. The gyrotron output is transmitted by conventional over-sized circular waveguides and converted to a two-dimensionally focused, linearly polarized, quasi-Gaussian beam, before it is injected into plasma. Scattered wave from plasma is received by horn antennas installed in the plasma vessel. It is converted into low frequency signal by a homodyne detection system.

The scattering measurements with scattering angles of 4.4° and 8.8° are carried out in NBI heated plasma and in "ion cyclotron resonance of frequency (ICRF)" heated plasmas. Fig. 16 shows a typical result of scattering measurement with the angle of 8.8° for NBI heated plasma. The trace shows one frequency spectrum of the scattered signal after another. Each spectrum covers the frequency band from 0 to 1 MHz and was obtained in 20 ms. The plasma is produced by a microwave pulse for electron cyclotron heating (ECH) and heated by a NBI pulse. As it is obvious, some broadening of the spectrum occurs during NBI heating. After the NBI pulse, the broadening cannot be observed. It is detected up to about 600 kHz, and is possibly due to scattering by drift waves excited spontaneously in the NBI heating phase.

Fig. 17 shows: a) a scattering measurement result for ICRF heated plasma, together with b) the corresponding reflection measurement using a reflectometer. The plasma is fired at the time of 10 ms by an ECH pulse, and an ICRF heating pulse is applied in the time interval from 40–90 ms. Each curve shows time evolution of scattered wave power for respective frequency interval. The scattering angle of 8.8° corresponds to wavenumber of 11.4 cm^{-1} . The increase in scattered wave power is observed during the ICRF heating. The results of the reflection measurement are in reasonable agreement with the scattering measurement and support the availability of both measurements.

Observed scattered signals suggest that some instability connected with the drift wave occurs during NBI or ICRF heating. This phenomenon will be dangerous for a good plasma confinement. We will continue the measurement under various plasma parameters to study the effect of this instability on plasma confinement.

B. Application to ESR Experiment [12], [28]

Gyrotrons FU I, FU E, and FU IVA are employed as radiation sources for ESR spectroscopy. The gyrotrons as

Fig. 17. (a) Time evolution of scattered wave power for respective frequency interval and (b) time evolution of reflected wave power for respective frequency interval.

Fig. 18. A block diagram of ESR spectrometer using Gyrotron FU I as a radiation source.

millimeter to submillimeter wave sources have important advantages, compared to other conventional sources; for example, frequency tunability in broad band and moderately high output power. Because of such advantages, our gyrotrons are useful for ESR spectroscopy in the millimeter to submillimeter wavelength range to study nonlinear phenomena of ESR.

Fig. 18 is a block diagram of an ESR spectrometer using Gyrotron FU I as a radiation source. The output power of the gyrotron is transmitted by an oversized circular waveguide and drives the spectrometer. The main part of the spectrometer is constructed using a W-band waveguide system. The superconducting magnet generates high magnetic field up to 8.5 T at the sample holder. The transmitted power is detected by a crystal detector.

Fig. 19 shows typical patterns demonstrating ESR resonant absorption for a standard sample, α , α -diphenyl- β -picryl hydrazyl (DPH). For a single crystal sample [Fig. 19(a)], a sharp resonance is observed. The half value width ΔH is equal to 2×10^{-4} T. The value is comparable with the theoretical prediction. On the other hand, for polycrystalline

powder sample, the resonance is broadened, because of an anisotropy of g value.

The measured resonance magnetic field H_0 is plotted in Fig. 20 as a function of the frequency ν . The solid line corresponds to the theoretical result. The ESR spectrometer using Gyrotron FU I as a radiation source covers a broad frequency band in millimeter wave region.

Fig. 21 shows observed half value widths of the resonance lines as functions of frequency ν . Hollow circles are the results for single crystal sample and solid circles for polycrystalline powder sample. Solid lines show theoretical predictions taking into account an anisotropy of g values. They are in good agreement with experimental results.

As another example, ESR of Cr^{3+} in dark ruby is measured using Gyrotron FU IVA as a radiation power source. Fig. 22 shows a typical ruby ESR spectrum obtained by sweeping the magnetic field. Absorption signals are observed at three different magnetic fields corresponding to fine structure transitions of the spin state interval ^4A ground state of the Cr^{3+} . Fine structure spectral lines for three transitions are observed on the

(a)

(b)

Fig. 19. ESR resonant absorption patterns for standard samples DPPH: (a) for a single crystal sample and (b) for polycrystalline powder sample.

 Fig. 20. The observed resonance fields H_0 as a function of the frequency ν .

spectrum. The two ESR signals around 3.2 T are for a DPPH (on the low magnetic field side) and for ruby (for the transition between $|+1/2\rangle$ and $|-1/2\rangle$), respectively. The resonant magnetic fields depend on the orientation of the c axis.

The field intensities H_0 corresponding to the resonant absorptions are plotted in Fig. 23 as functions of the angle

 Fig. 21. The observed half value widths of the resonant absorption lines as functions of the frequency ν . Solid lines show theoretical predictions taking an anisotropy of g values into account.

 Fig. 22. ESR spectrum of $\text{Cr}^{3+}(^4A)$ in ruby as a function of magnetic field H_0 at $\nu = 167.62$ GHz. ESR signal around 6.0 T is DPPH's one as a correct marker of the field.

θ between the directions of the magnetic field and the c axis of ruby. Solid curves are calculation results, where g factors, and the fine structure constant D are determined for the best fit with the experimental results, as follows:

$$g_{\parallel} = 1.9803, \quad g_{\perp} = 1.9813, \quad \text{and} \quad D = -5.742 \text{ GHz.}$$

Figs. 24 and 25 show the frequency dependence of the g factors and the fine structure constants, respectively. Solid curves are calculation results using a formula including ν^2 terms. It seems that the experimental results are in good agreement with the calculation results. ESR studies at higher frequency help to understand the variations in g factors and in the D value.

We will try the ESR experiment in a near future in a broad frequency band in submillimeter wave region. We are now preparing a pulse magnet for a submillimeter wave ESR spectrometer. Its intensity can rise up to about 30 T.

IV. SUMMARY

Gyrotron FU series in Fukui University consists of seven gyrotrons. Each of them is designed to get many single mode operations on fundamentals, second, and even third harmonics

Fig. 23. The angular dependence of the three ESR transition lines of $\text{Cr}^{3+}({}^4\text{A})$ in ruby. Solid lines are calculation results by third order perturbation on the Price Hamiltonian.

Fig. 24. g values of $\text{Cr}^{3+}({}^4\text{A})$ in ruby versus the resonance frequency.

Fig. 25. The fine structure constant D of $\text{Cr}^{3+}({}^4\text{A})$ in ruby versus the resonance frequency. Solid lines are calculation results, supposing that the frequency dependence of D is proportional to ν^2 .

of electron cyclotron resonance. Such a design results in high frequency, medium power gyrotrons covering broad frequency band from millimeter to submillimeter wave region. The results achieved by our gyrotrons are summarized as follows.

- 1) These gyrotrons have achieved frequency tunability from 38–889 GHz.

- 2) The output powers are moderately 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.
- 3) Higher harmonic operation is demonstrated up to the fourth harmonic. This is necessary for development of high frequency gyrotrons covering the whole submillimeter wavelength range.
- 4) Mode competition and mode cooperation between the fundamental and the second harmonic are studied in detail. A mode competition is not convenient for our high frequency, harmonic gyrotron. Therefore, it should be avoided.
- 5) Amplitude modulation, frequency step switching, and frequency modulation of gyrotron output were achieved for its application in various new areas.
- 6) Complete CW operation has been performed with high stability of amplitude and frequency of the gyrotron output.

Gyrotron FU II has already been employed for plasma scattering measurements on CHS in NIFS, and Gyrotron FU I, FU E, and FU IVA for ESR experiments to study the resonance line widths of DPPH and frequency dependencies of g factors and a fine structure constant D of ruby.

At present, the newest gyrotron Gyrotron FU V has just been designed and constructed. The gyrotron consists of a helium-free 8 T superconducting magnet and a demountable tube. It should achieve time-unlimited, high quality mode operation for applications in far infrared spectroscopy.

ACKNOWLEDGMENT

The authors wish to thank Dr. G. F. Brand from the University of Sydney, Prof. M. Thumm from Forschungszentrum Karlsruhe, and Dr. W. Kasperek and Dr. D. Wagner from Universität Stuttgart for their invaluable discussions.

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