Development of 394.6 GHz CW Gyrotron (Gyrotron FU CW II) for DNP/Proton-NMR at 600 MHz

Development of 394.6 GHz CW gyrotron (Gyrotron FU CW II) for DNP/proton-NMR at 600 MHz

T. Idehara, I. Ogawa, La Agusu, T. Kanamaki, S. Mitsudo, T. Saito

Research Center for Development of Far Infrared Region, University of Fukui

Bunkyo 3-9-1, Fukui-shi 910-8507, Japan

T. Fujiwara, H. Takahashi

Institute of Protein Research, Osaka University,

3-2 Yamadaoka, Osaka, Japan

Abstract

Gyrotron FU CW II with an 8 T liquid He free superconducting magnet, the second gyrotron of the THz Gyrotron FU CW Series, has been constructed and the operation test was successfully carried out. It will be used for enhancing the sensitivity of 600 MHz proton-NMR by use of Dynamic Nuclear Polarization (DNP). The designed operation mode of the gyrotron is $TE_{2,6}$ at the second harmonic. The corresponding frequency is 394.6 GHz. The real operation frequency is 394.3 GHz at TE_{06} mode, because of fabrication error of the diameter of the cavity. The operation is in complete CW at the output power of around 30 W or higher at the TE_{06} cavity mode. There are many other operation modes at the fundamental and the second harmonic. Typical output power of the fundamental and the second harmonic are higher than 100 W and 20 W, respectively. The highest frequency observed up to the present is 443.5 GHz at the second harmonic operation of $TE_{6,5}$ mode. The measured results are compared with the theoretical consideration.

Key words: gyrotron, THz, DNP, NMR, CW operation, second harmonic

1. Introduction

Gyrotrons are useful and important high power radiation sources in millimeter to submillimeter wavelength range, which includes sub-THz and THz frequency region. Untill quite recently, we had no radiation source with high power and high stability in this frequency range. Gyrotrons appeared as high power radiation sources which cover the so-called 'THz gap'.

The major part of the gyrotron development began in 1970s for ultra-high power millimeter wave gyrotrons. These gyrotrons were used mainly for heating and current drive of fusion plasma.[1] The output power per one tube is 1.5 MHz and the frequency is ranged from140 GHz to 170 GHz. The operation pulse width is extended up to 3000 sec.

The development of high frequency gyrotrons with high field superconducting magnets is rather a minor way of the gyrotron development. It was carried out in several research institutes, that is, IAP RAS, MIT, the University of Sydney and the University of Fukui. The frequency range of submillimeter waves is achieved in 1980s and 1990s by several gyrotrons in these institutions. [2)-7)]

In the Research Center for Development of Far Infrared Region, University of Fukui (FIR FU), we have developed high frequency Gyrotron FU Series which consists of nine gyrotrons. Among them, in 1996, Gyrotron FU IVA achieved the frequency of 889 GHz with the output power of around 100 W. The frequency corresponds to the wavelength of 377 μm. [8)] This frequency was the long-term world record for high frequency operation of gyrotron untill 2006. Recently, our pulsed gyrotron with a high field pulse magnet achieved the breakthrough of 1 THz by the second harmonic operation at the field intensity of 19.1 T.[9)]

Now, we are developing the THz Gyrotron FU CW Series, which will cover sub-THz to THz range and operate in a complete CW mode. Gyrotron FU CW I with a 12 T liquid He free magnet has already been developed and succeeded in fundamental operation at 300 GHz with the output power of 1.75 kW. [10),11)] It is being applied to material processing and the development of new medical technology.

The second gyrotron in the FU CW series, Gyrotron FU CW II with an 8 T liquid He free magnet, has also been constructed and succeeded in operation test. It will be used for enhancement of NMR sensitivity by use of DNP. In this manuscript, the details of the gyrotron are presented. The design of the gyrotron on the basis of computer simulation is described in the next section.[11)] The whole experimental device including a demountable gyrotron tube constructed following the design is introduced in the third section. Experimental results and comparison with the computer simulation results are presented in the fourth section and finally the contents described in the manuscript will be summarized in the fifth section.

2. **Design of the gyrotron tube on the basis of computer simulation**

The goal of this design is to successfully generate several tens watts of CW power at the second harmonic operation of $TE_{2,6}$ mode at 394.6 GHz, with a power level which is sufficient to perform biological experiments using sensitivity-enhanced nuclear magnetic resonance (NMR) through dynamic nuclear polarization (DNP).

It was well-known that the second harmonic modes are much more difficult to be excited than the fundamental mode because of mode competition with fundamental modes. The mode competition of TE_{26} mode with neighbor fundamental mode TE_{23} was studied in detail experimentally.[4)] This means that we have much experience about this and are a good understanding of how to excite this mode.

The gyrotron is designed for several-day-long operation at a low level of output power. It is designed for 25 keV or less electron beam energy. The electron gun for generating helical electron beam is a triode type electron gun. The cathode radius is 4.5 mm. In practice, the electron beam parameters such as the beam radius and the velocity pitch factor can be experimentally tuned by using a gun coil installed around the electron gun through changing the magnetic compression rate, that is, the ratio between axial magnetic fields at the cavity and cathode. The gun coil produces the maximum magnetic field of 0.183 T.

The resonant interaction structure of gyrotron is a cylindrical cavity that is optimized for the $TE_{2,6}$, second harmonic mode at 394.6 GHz using a cold cavity (electron beam absent) simulation code. Fig. 1 shows the crosssection of a cylindrical cavity consisting of a straight section of 15 mm in length and circular cross-section which has a radius of 2.36 mm joined to a

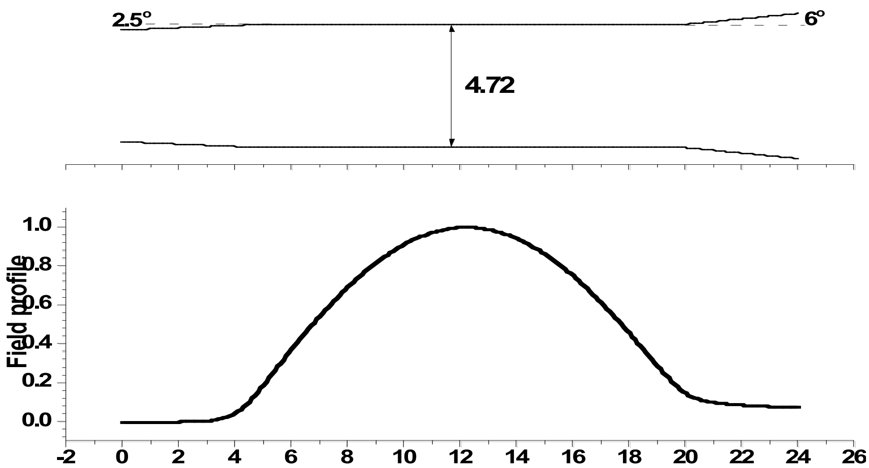

Fig. 1 Cross-section of a 395 GHz gyrotron cavity with the axial field profile for the second harmonic $TE_{2,6}$ mode. Input taper: L_1 = 4 mm, θ_1 = 2.5°; Middle section R = 2.36 mm, L = 15 mm; output taper: L_2 = 4 mm, θ_2 = 6.0°.

linear up-taper section with a slope angle of 6.0° at the outlet of the cavity and a linear down-taper section with the angle of 2.5° at the entrance of the cavity. The lower trace in Fig. 1 shows the axial profile of the designed mode, $TE_{2,6}$. The material of the gyrotron cavity is copper.

Fig. 2 demonstrates the starting current of all modes in the cavity in the magnetic field range of 6.7 T to 7.5 T. It is seen that there are several candidates for single mode operations at the second harmonic, if the magnetic field intensity is adjusted carefully. For single mode operation of $TE_{2,6}$ and $TE_{0,6}$ at the second harmonic, the most dangerous competitor is $TE_{2,3}$ mode at the fundamental. Mode competition among these modes has been simulated. It was confirmed as the results that both modes $TE_{2,6}$ and $TE_{0,6}$ can overcome $TE_{2,3}$ and excited in single modes.

The design details were already published in the previous paper.[12)]

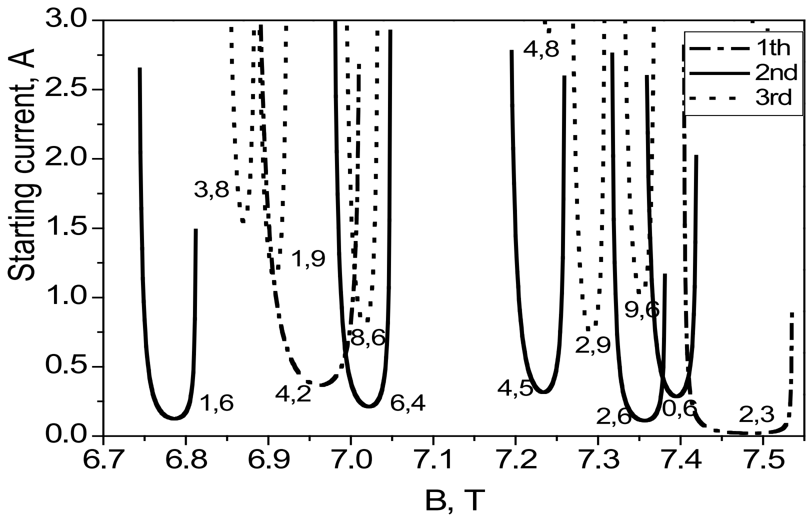

Fig. 2 The starting currents for the resonant cavity with the magnetic field range from 6.7 T to 7.55 T. The fundamental, second, and the third harmonics correspond to the broken, solid, and dotted lines, respectively

3. Experimental apparatus

The gyrotron FU CW II device consists of a demountable gyrotron tube, a magnet system consisting of a 8 T liquid He free superconducting magnet and three additional coils in the gun region with a power supply, two high voltage power supplies for the cathode and the anode of electron gun and a power supply for a filament of the gun.

The gyrotron tube is installed on the center axis of the air bore of the cryostat whose diameter is 100 mm. The tube is demountable. Therefore, all of the components, that is, an electron gun, a cavity system, a collector and a window, can be replaced, when we need to change any of them. The electron gun is a triode magnetron injection gun. The radius of the emitting area is 4.5 mm. A cavity is located in the center of the superconducting magnet coil. The maximum field intensity at the cavity region is 8 T and the variation in the spherical region with the diameter of 10 mm is less than 1 percent. Two water jackets are installed on the cavity and the collector regions in order to cool down these regions during CW operation. The output window is made of a sapphire disk whose diameter and thickness are 33 mm and 2.5 mm, respectively. The inner diameter of the collector is 28 mm. It operates as an oversized waveguide for transmitting an output power from the outlet of cavity to the window. After the window, a circular waveguide with a diameter of 28 mm is connected to the collector cylinder across the sapphire window disk.

Photo.1 The appearance of Gyrotron FU CW II

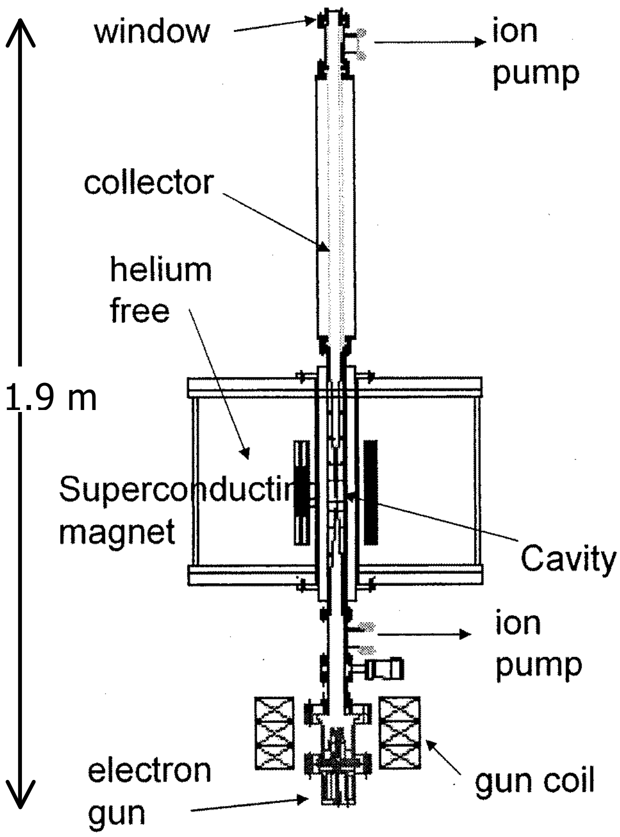

Fig. 3 Installation of a demountable tube on the center axis of an 8 T liquid He free magnet

Photo.1 shows the appearance of the gyrotron tube and the magnet system, and Fig. 3 shows a view of the cross section. A demountable tube is installed on the axis of the magnet system consisting of an 8 T superconducting magnet and three additional coils.

Three pieces of normal copper coils surround an electron gun in order to control the field intensity at the gun region and then to adjust the best value injection point of beam electrons at the entrance of a cavity. In addition, the anode voltage is controlled in order to adjust the best condition of the pitch factor. These are quite important to achieve highly efficient operation of the gyrotron. In almost all cases, a mirror ratio of the field configuration, that is, the ratio between the field intensities at the cavity region and the gun region, can vary from 40 to 80. .

The magnetic field intensity at the cavity region varies from 2 T to 8 T, the beam electron energy from 8 kV to 15 kV and the beam current from 200 mA to 400 mA. The gyrotron is operated at both pulsed and continuous modes. In the case of pulsed operation mode, repetition rate is typically 1 Hz and the pulse width varies from 1 ms to 500 ms. After completing the vacuum inside the tube in a pulsed operation, the operation is changed to the continuous mode.

4. Experimental results and comparison with the computer simulation results

First of all, we have measured radiation power from the gyrotron as function of magnetic field intensity. The operation is in a pulsed mode. The repetition rate is 1 Hz and the duty ratio typically 10 to 30 percent. The pulsed output radiation power is sampled and recorded on an XY recorder. Fig. 4 shows the results. In the upper trace, radiation power measured directly after the window is traced as a function of magnetic field intensity, while in the lower trace, radiation power coming out through a high-pass filter with a small circular waveguide is traced as a function of the field intensity. The diameter and the cutoff frequency are 0.7 mm and 251 GHz, respectively. Therefore, the upper trace includes both the fundamental and the second harmonic radiations, while the lower trace only second harmonics. As seen in the figure, the widths of radiation peak in the lower trace (second harmonics) are much narrower than those in the upper trace (mainly fundamentals). Some of the radiation peaks in the lower trace are seen in the upper trace at the same magnetic field intensity. This means that these second harmonic operations occur in single modes without mode competition with any fundamental operation modes. These features are predicted by the computer simulation demonstrated in our previous paper,[12] and are very important for our high frequency, harmonic gyrotron. Almost all radiation peaks appearing in the both traces correspond to cavity modes whose mode numbers have been identified by observed frequencies.

Next, the operation mode switched from pulsed mode to CW mode. Output power just after the output window for all of observed radiation peaks is measured by use of a water load. The results are shown in Tables 1 and 2. Observed powers are distributed in the ranges of 100 to 200 W for fundamental operations and 10 to 30 W for second harmonic operations. All of these powers are obtained by single mode CW operations even in the cases of second harmonics. Therefore, these are useful and convenient for its application to many new technologies in the

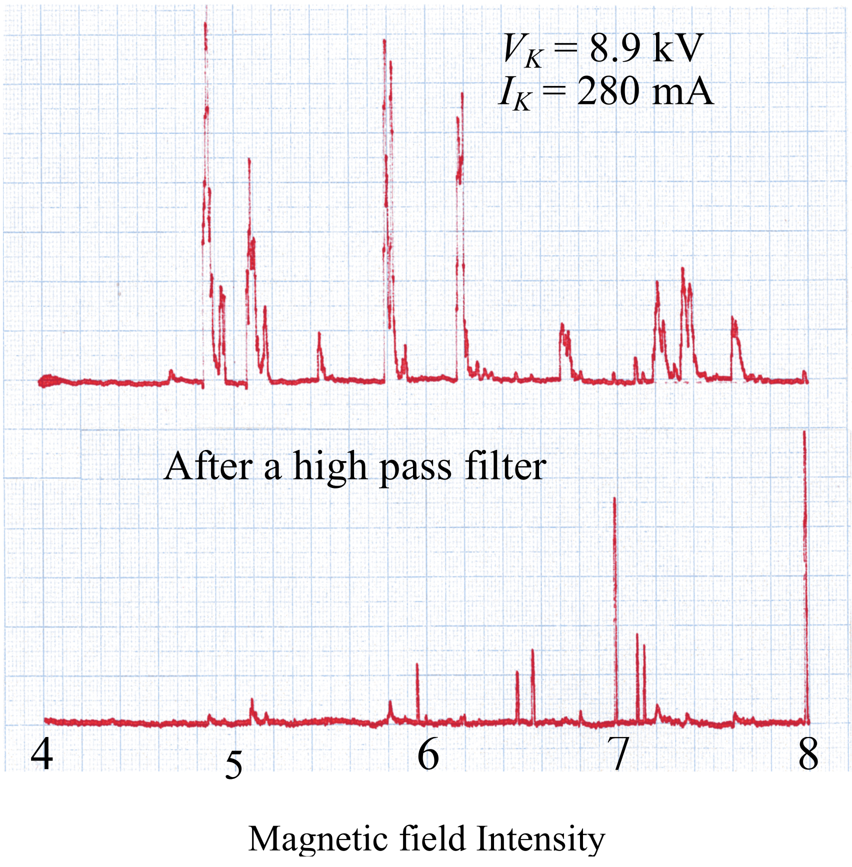

Fig. 4 Radiation power from the gyrotron FU CW II as functions of magnetic field intensity. Upper trace: Radiation power measured just after the output window. Lower trace: Radiation power coming out through the high pass-filter with a thin circular waveguide whose diameter is 0.7 mm. (The corresponding cutoff frequency is 251 GHz.)

sub-THz frequency range.

The frequencies for all of radiation peaks in both the fundamental and the second harmonic operations are measured by a spectrum analyzer with a heterodyne detection system which consists of a synthesizer as a local oscillator and a harmonic mixer. From this measurement, the cavity modes can be identified and listed in both tables. In the tables, azimuthal and radial mode numbers m and n are shown. The results of frequency measurement are shown as f_{meas} in Tables 1 and 2 with the calculated frequencies as f_{cal} for the designed cavity.

Table 1 Operation parameters of gyrotron FU CW II at the fundamentals (N=1). Here, are demonstrated the main field intensity B_0 in T at the cavity region, observed output power P in W, acceleration voltage for electrons V_b in kV, electron beam current I_b in mA, beam efficiency μ in %, calculated frequency f_{cal} in GHz for cavity mode, measured frequency f_{meas} in GHz and corresponding cavity mode number m,n.

B_0,T	P,W	V_b,kV	I_b,mA	μ,%	f_{cal},GHz	f_{meas},GHz	$TE_{m,n}$	N
3.86	130	9.74	260	5.1	108.10	107.48	1,2	1
4.84	210	9.68	320	6.8	138.84	134.95	2,2	1
5.10	95	9.68	320	3.1	142.79	141.28	0,2	1
5.83	100	9.72	280	3.7	162.27	161.34	3,2	1
6.19	158	9.69	310	5.3	172.79	171.73	1,3	1
6.74	126	9.71	290	4.5	187.87	186.65	4,2	1
7.22	180	9.79	210	8.8	201.75	200.43	2,3	1
7.38	170	9.82	180	9.6	205.87	204.54	0,3	1
7.62	181	9.81	190	9.7	212.87	211.40	5,2	1

Table 2 Operation parameters of gyrotron FU CW II at the second harmonics (N=2). Demonstrated operation parameters are the same as those in Table1.

B_0,T	P,W	V_b,kV	I_b,mA	μ,%	f_{cal},GHz	f_{meas},GHz	$TE_{m,n}$	N
6.9860	17.9	9.62	380	0.49	388.20	386.03	4,5	2
7.15	24	13.66	340	0.52	394.6	392.25	2,6	2
7.19	32	13.675	325	0.72	396.69	394.27	0,6	2
7.98	5.3	9.62	380	0.14	443.51	440.93	6,5	2

As seen in the tables, all of measured frequencies are lower than calculated frequencies by about 0.57 percent. This differences come from the fabrication error of the cavity radius. The error is also 0.57 percent and real size of the radius is larger by 14 μm. The frequency of $TE_{0,6}$ mode at the second harmonic opration shown in Table 2 is close to the principally designed frequency, that is, 394.6 GHz of TE_{26} mode. The output power is larger than 30 W. This means that the output power of this mode is available as a radiation source for 600 MHz DNP/ proton-NMR. Many other observed frequencies are also useful for sub-THz spectroscopy, for example, ESR measurement, plasma diagnostics and so on. All frequencies observed up to the present are plotted as functions of magnetic field intensity in Fig. 5.

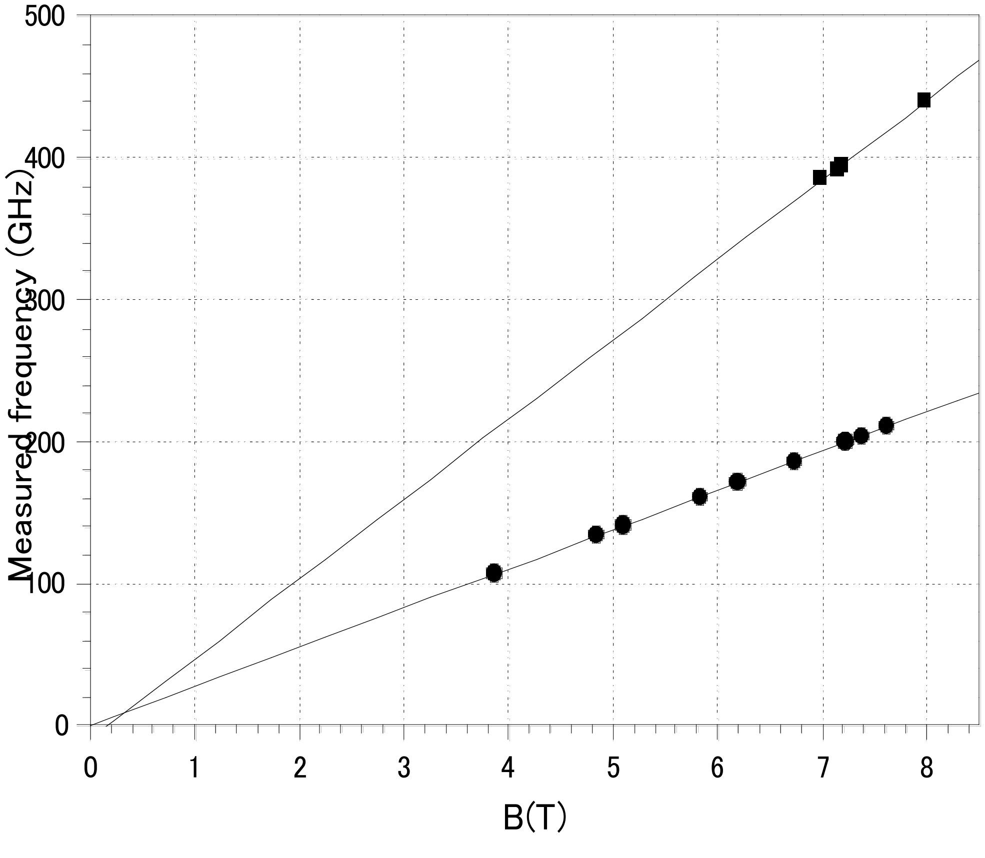

Fig. 5 All of observed frequencies as functions of magnetic field intensity.

The beam efficiency μ is estimated by dividing the measured output power P by the input power of electron beam $V_b \cdot I_b$ and demonstrated in Tables 1 and 2. It ranges from 3 to 10 percent for fundamental operations and from 0.1 to 0.7 percent for second harmonic operations.

The efficiency at the fundamentals is quite high even at low voltage operation lower than 10 kV.

Next, we tried to measure the dependency of output power P on the beam current I_b for several operation modes, $TE_{2,3}$ at the fundamental, $TE_{2,6}$ and $TE_{0,6}$ at the second harmonic. The beam electron energy is kept at the constant values of around 9 keV and 14 keV, respectively. The measurement results are shown in Fig. 6. It seems that output power for all modes is saturated even at low beam current I_b around 300 mA. In the present case, the beam electron energy is low: around 9 keV for fundamentals and around 14 keV for second harmonics. The low saturation level may result from such low beam electron energy. Hopefully, it will be increased by increased beam electron energy V_b.

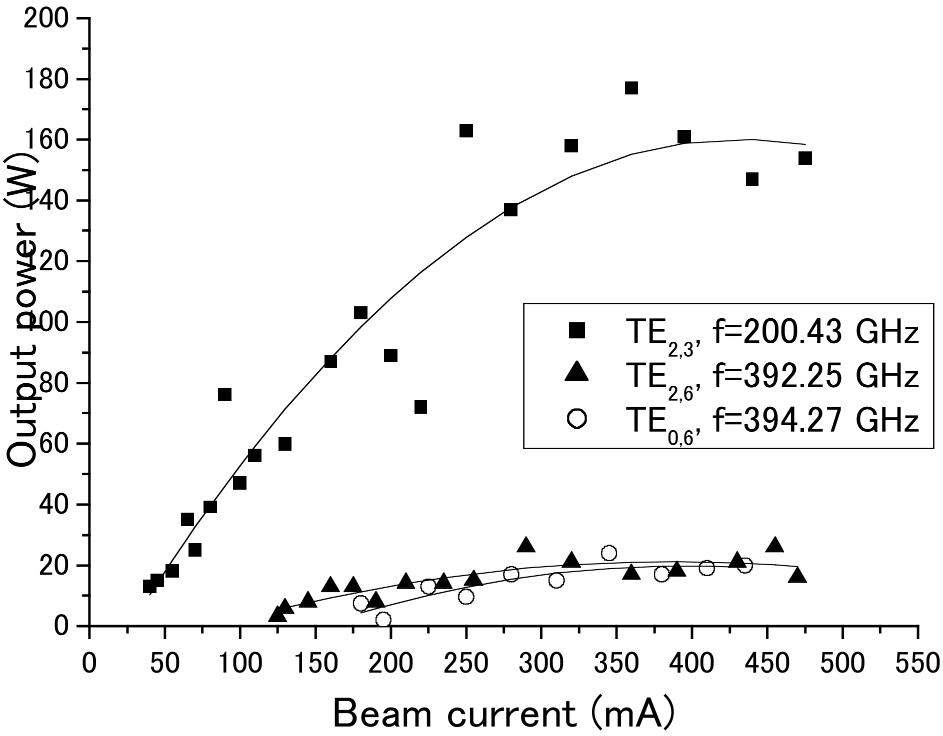

Fig. 6 Observed output power P for $TE_{2,3}$ mode at the fundamental, $TE_{2,6}$ and $TE_{0,6}$ modes at the second harmonics as functions of beam current Ib.

Fig. 7 shows a typical frequency spectrum for $TE_{0,6}$ mode operation at the second harmonic. (The frequency is 394.27 GHz.) A heterodyne detection system with a synthesizer as a local oscillator and a harmonic mixer are used for the measurement. The frequency is quite stable.

The fluctuation is an order of 10 kHz. The quality of the spectrum is also excellent. As seen in Fig. 5, the half value width is several kHz and the width for 10 dB lower is around 10 kHz. This means that gyrotron FU CW II can be available for spectroscopy with high frequency resolution.

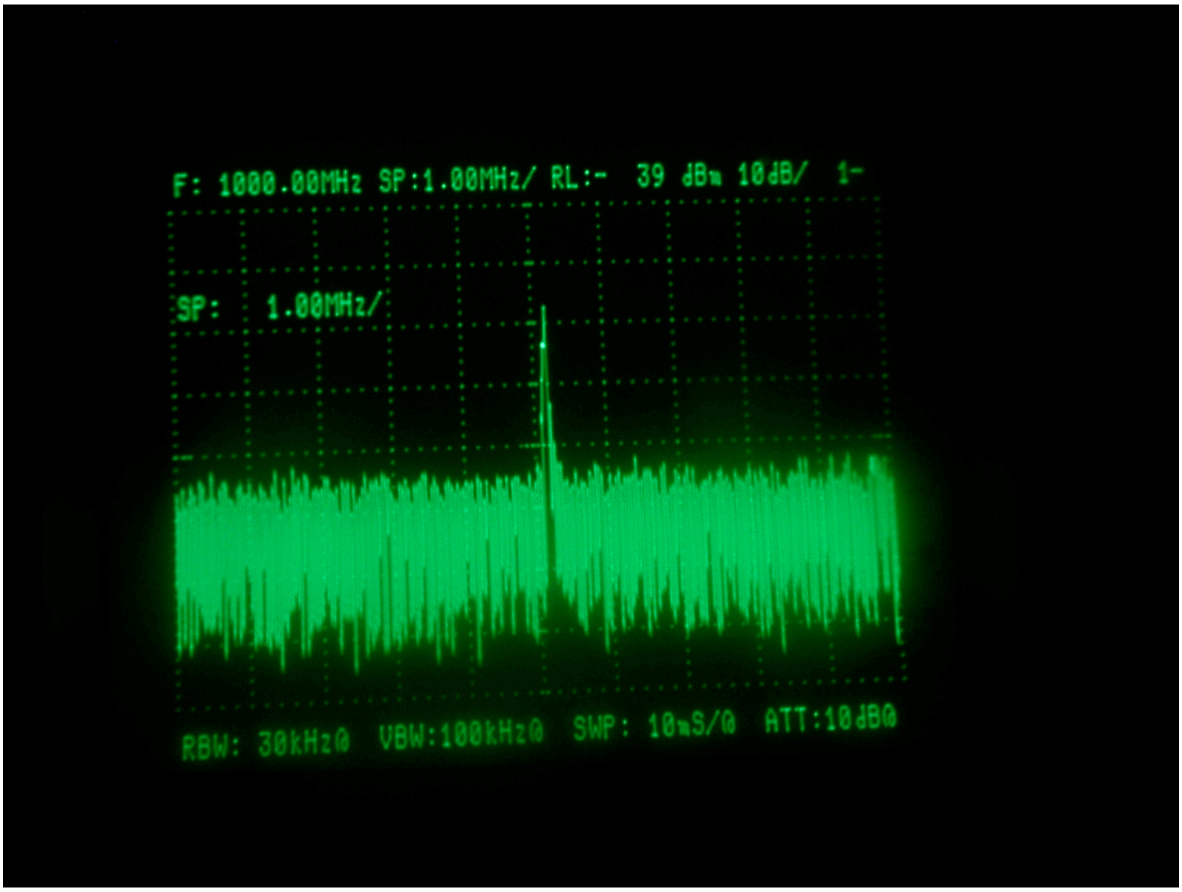

Fig. 7 A frequency spectrum for TE_{06} mode operation at the second harmonic. Horizontal: 1 MHz/div. Vertical: log scale.

5. Conclusion

A 394.6 GHz CW gyrotron (Gyrotron FU CW II) is designed for application to 600 MHz DNP/ proton-NMR for sensitivity enhancement, which will be used for analysis of protein molecules. The corresponding frequency for ESR is 394.6 GHz. The required output power is several tens to one hundred watts. In addition, high stabilization of frequency and amplitude for long-term CW operation are also requested. Therefore, such requirements decide the specifications of the gyrotron.

We decided to use a single mode operation of $TE_{2,6}$ mode at the second harmonic. After the construction of the gyrotron tube, it is tested by using an 8 T liquid-He free superconducting magnet.

Many cavity modes including $TE_{2,6}$ can operate at both the fundamentals and second harmonics. Among them, several modes at the second harmonics operate in single modes. The output power measured by a water load is distributed in the ranges of 100 to 200 W for fundamental operations and of 10 to 30 W for second harmonic operations. The frequencies are also measured by a heterodyne detection system with a synthesizer and a harmonic mixer. All of measured frequencies are lower than the calculated ones by around 0.57 percent. This means that there is the fabrication error of the cavity. The error is also 0.57 percent and the real size of the cavity radius is larger by 14 μm. As the results, $TE_{0,6}$ mode (not $TE_{2,6}$) is the best mode for application to 600 MHz DNP/ proton-NMR, because the frequency 394.27 (close to 394.6 GHz) and the output power is around 30 W. A slight difference between the observed frequency 394.27 GHz) and the required frequency (394.6 GHz) should be cancelled out by adjusting the magnetic field intensity of 600 MHz proton- NMR device.

The quality of the observed frequency spectrum of TE_{06} mode is quite high and the stability of the frequency is excellent. All of observed cavity modes are useful and available for high power sub-THz technologies including ESR spectroscopy, DNP/NMR for analysis of protein molecules, plasma scattering measurement and so on.

We are now trying higher voltage operation of the gyrotron FU CW II in order to increase the output power. In the future, we are planning the long term, stable operation of the gyrotron.

Acknowledgements

This work was carried out as a collaborative research work between Institute of Protein Research, Osaka University and the Research Center for Development of Far Infrared Region, University of Fukui. Japan Science and Technology Agency (JST) supports this work by the SENTAN project for ‘Development of System and Technology for Advanced Measurement and Analysis’.

References

1) M. Thumm, “State-of-the-Art of High Power Gyro-Devices and Free Electron Masers Update 2006,” Scientific Report FZKA 7289, Forschungszentrum Karlsruhe, Germany, February 2007

2) G.F. Brand, Z. Chen, N.G. Douglas, M. Cross, J.Y.L. Ma and L.C. Robinson, A tunable

millimeter-submillimeter gyrotron, Int. J. Electronics **57** (1984) 863-870.

3) S.E. Spira-Hakkarainen, K.E. Kreischer and R. J. Temkin, Submillimeter-wave harmonic gyrotron experiment, IEEE Trans. Plasma Sci., PS-18 (1990) 334-342.

4) T. Idehara, T. Tatsukawa, I. Ogawa, H. Tanabe, T. Mori, S. Wada, G.F. Brand and M.H. Brennan, Development of a Second Cyclotron Harmonic Gyrotron Operating at Submillimeter Wavelengths, Phys. of Fluids **B4** (1992) 267-273

5) V.A. Flyagin, A.G. Luchinin, G.S. Nusinovich, Submillimeter-wave gyrotrons: theory and experiment, Int. J. Infrared and Millimeter Waves **4** (1983) 629-637.

6) T. Idehara, T. Tatsukawa, I. Ogawa, Y. Shimizu, and T. Kanemaki, Development of a High-Frequency, Second-Harmonic Gyrotron Tunable up to 636 GHz, Phys. of Fluids **B5** (1993) 1377-1379.

7) K.D. Hong, G.F. Brand and T. Idehara, A 150-600 GHz Step-Tunable Gyrotron, J. Appl. Phys. **74** (1993) 5250-5258.

8) T. Idehara, S. Mitsudo and I. Ogawa, Development of high frequency, high stable gyrotrons as millimeter to submillimeter wave radiation sources, IEEE Trans. Plasma Sci. **32** (2004) 910-916.

9) T. Idehara, H. Tsuchiya, O. Watanabe, La Agusu and S. Mitsudo, First experiment of a THz gyrotron with a pulse magnet, Int. J. Infrared and Millimeter Waves, **27**, pp. 319-331 (2006).

10) V. E. Zapevalov, V. K. Lygin, O. V. Malygin, M. A. Moiseev, V. P. Karpov, V. I. Khizhnjak, E. M. Tai, T. Idehara, I. Ogawa, S. Mitsudo, Development of the 300 GHz/4 kW/CW gyrotron, Proc. of Int. Workshop on Strong Microwave in Plasmas, **1** (2006) pp. 167-172.

11) T. Saito, T. Idehara, S. Mitsudo, I. Ogawa, H. Hoshizuki, H. Murase, K. Sakai, Oscillation Characteristics of CW 300 GHz Gyrotron FU CW I, Conf. Digest of The Joint 31 st International Conference on Infrared and Millimeter Waves and 14 th International Conference on Terahertz Electronics (IRMMW –THz 2006) Shanghai, China, September 18-22, 2006

12) La Agusu, T. Idehara, T. Saito, H. Murase, T. Kanemaki, D. Takahashi, and T. Fujiwara, Design of a CW 395 GHz gyrotron (Gyrotron FU CW II) for sensitivity enhancemernt of NMR spectroscopy, Int. J. Infrared and Millimeter Waves, to be published.