Development of terahertz FUCW gyrotron series for DNP

Development of THz gyrotrons FU CW Series for DNP/NMR

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Abstract- The new gyrotron series in FIR FU, so-called Gyrotron FU CW Series, is being developed for application to high power THz technologies. The second gyrotron, of the series, Gyrotron FU CW II with an 8 T liquid He-free superconducting magnet 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 designed 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 harmonics. Typical output power of the fundamental and the second harmonic are higher than 100 W and 20 W, respectively. The third gyrotron, Gyrotron FU CW III with 20 T superconducting magnet has already been constructed and the operation test has been almost completed. The highest frequency is around 980 GHz at the second harmonic operation. This gyrotron demonstrates a possibility of application to higher frequency DNP/NMR up to 1 GHz.

1 Introduction

High power millimetre wave gyrotrons are being developed actively in the world for application to plasma heating and current drive of large-scale tokamaks for thermonuclear fusion research. Recently, one of such gyrotrons has achieved a long term CW operation at a high power level of 1 MW.[1)]

On the other hand, high frequency gyrotrons covering sub-THz to THz range are also being developed for application to high power THz technologies in material science and technology, biological and medical science, etc. Several gyrotrons has already achieved high frequency operations in submillimeter wavelength region.[2)-4)] Gyrotron FU Series in FIR FU has succeeded in the operation at high frequencies up to 0.89 THz by using a 17 T magnet and the second harmonic mode. This frequency was a long term world record for high frequency operation of gyrotron. Recently, a gyrotron in FIR FU with a 21 T pulse magnet achieved the breakthrough of 1 THz.[5)] In the gyrotron, a demountable gyrotron tube is installed on the center axis of 21 T pulse magnet. In the operation test, a high voltage pulse is applied to electron gun installed in the region of the additional coils for controlling the injection point of electron beam in the cavity region. When B in the cavity region is changed, many cavity modes are excited at the fundamentals and second harmonics of electron cyclotron frequency. The second harmonic radiation is separated from the fundamental by using a high pass filter. Observed frequencies range from 395 GHz to 1,016 GHz. The maximum frequency 1,016 GHz is achieved by the second harmonic operation of $TE_{4,12}$ cavity mode. This is a new world record for high frequency operation of gyrotron. Corresponding field intensity B is 19.1 T. Now we are trying to increase the frequency by increasing B.

For the convenience of the application, continuous wave (CW) gyrotrons (Gyrotron FU CW Series) are being developed. Gyrotron FU CW I has been developed and succeeded in the CW operation at 300 GHz under high power of 1.7 kW. The next gyrotrons, Gyrotron FU CW II[6)] and III[7)] have also been developed. The parameters are as follows: around 400 GHz, 100 W for Gyrotron FU CW II and 1 THz, 100 W for Gyrotron FU CW III under CW operation. These gyrotrons will be used for development of high power THz technologies, for example, plasma diagnostics, DNP-NMR for protein research, etc. A similar CW gyrotron was developed in MIT for DNP-NMR experiment.[8),9)]

2 Gyrotron FU CW II

We have already finished the construction of Gyrotron FU CW II[6),10)] and almost completed the operation test. Fig. 1 shows a cross section of the gyrotron and Photo 1 does a side view. The gyrotron consists of an 8 T He-free superconducting magnet, a demountable tube, a vacuum pump system and power supplies. The cavity is a simple cylindrical one whose diameter and length are 5.72 mm and 15 mm. The designed frequency is 394.6 GHz at the second harmonic operation of TE_{26} cavity mode. After completing the operation test, the gyrotron will be used for enhancement of NMR sensitivity by use of Dynamic Nuclear Polarization (DNP).[8)] 394.6 GHz is corresponding to ESR frequency at the field intensity of around 14 T. The frequency of proton NMR at the field is 600 MHz.

We have already succeeded in the operation test of the gyrotron at many fundamentals and second harmonics.

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. 2 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 of the waveguide is 0.7 mm. A corresponding cut-off frequency for TE_{11} mode is 251 GHz. Therefore, any radiation with the frequency below 251 GHz is not able to

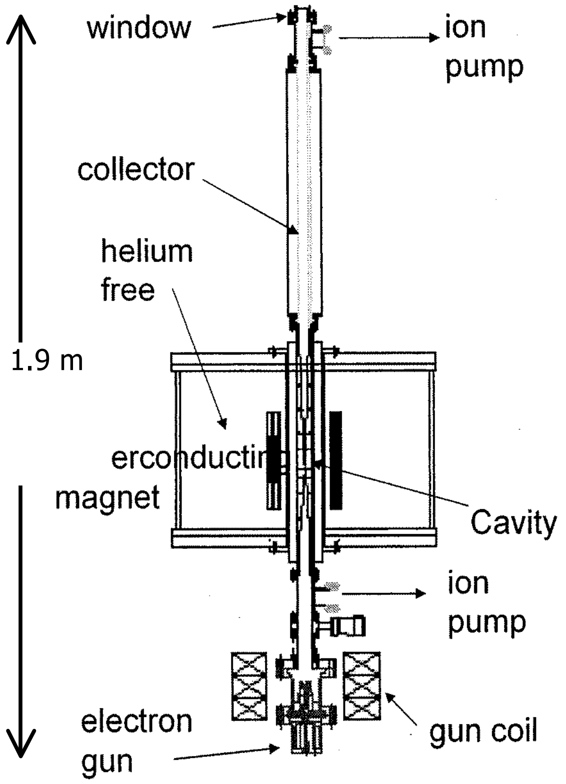


Fig. 1 A cross section of Gyrotron FU CW II

Photo. 1 A side view of Gyrotron FU CW II

transmit the waveguide and it can operate as a high-pass filter. 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,[10)] and they are very important for our high frequency, harmonic gyrotron. Some other peaks are overlapping on more powerful fundamental radiation peaks observed in the upper trace. Therefore, these radiations are not single mode operations at the second harmonics. Almost all radiation peaks appearing in the both traces correspond to cavity modes whose mode numbers have been identified by measured frequencies. In addition, measured frequencies for all of radiation peaks appearing in the lower trace are higher than 251 GHz. This means that the thin waveguide acts as a high-pass filter.

Three peaks appearing in the lower trace near 7 T are quite important, because corresponding frequencies are close to 400 GHz. The magnetic field range near 7 T is

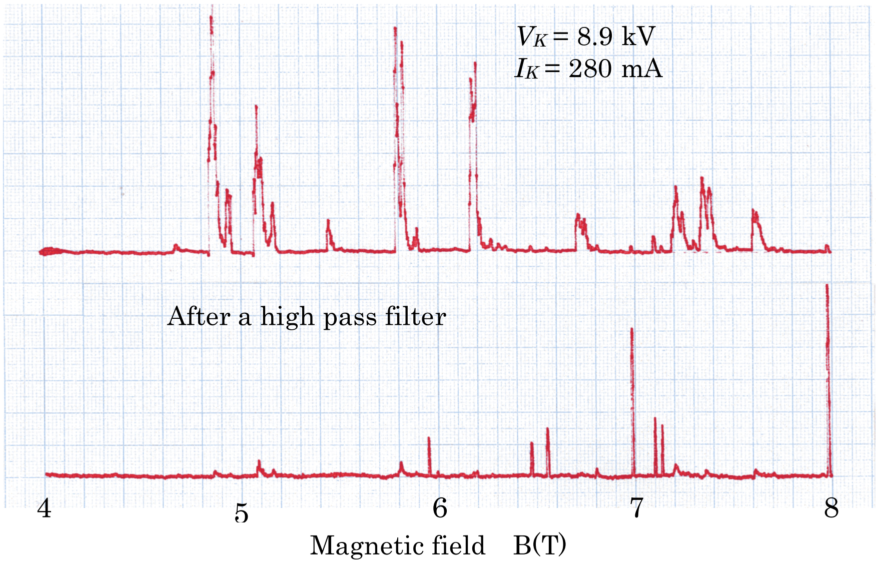


Fig. 2 Radiation power from the Gyrotron FU CW II as functions of magnetic field intensity. Upper trace: Radiation power measured just after the output window. Lower trace: Radiation power coming out through the high pass-filter with a thin circular waveguide whose diameter is 0.7 mm. (The corresponding cutoff frequency is 251 GHz.) Acceleration voltage of electron beam Vk=8.9kV, electron beam current Ik=280 mA.

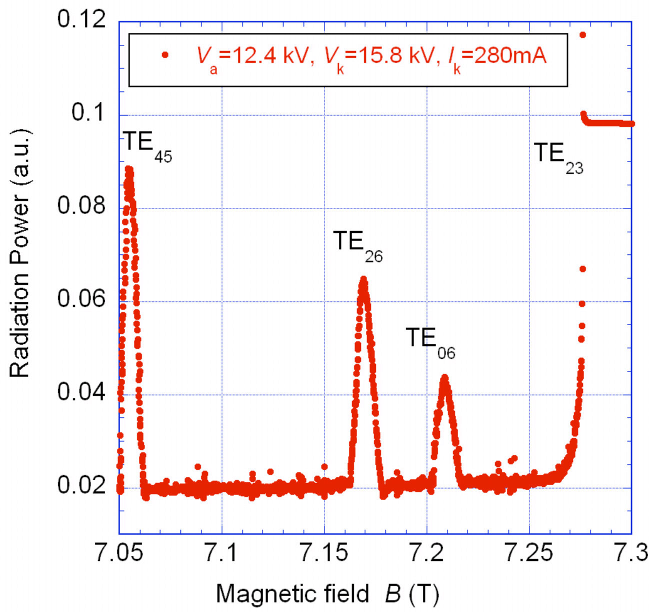


Fig. 3 Three radiation peaks at second harmonic operations of $TE_{4,5}$, $TE_{2,6}$ and $TE_{0,6}$ and one peak near 7.3 T at fundamental operation of $TE_{2,3}$ are shown as function of magnetic field B. Acceleration voltage of electron beam Vk=15.8kV, electron beam current Ik=280 mA and Anode voltage Va=12.4 kV.

extended and shown in Fig. 3. Here, three peaks for second harmonic operations and one for fundamental operation are observed. Corresponding cavity modes are $TE_{4,6}$, TE_{26} and TE_{06} for second harmonic operations and TE_{23} for a fundamental operation. All of these four operations look stable. Among those, the radiation peak of TE_{06} mode is the most important, because the measured frequency is 394.3 GHz. This can be used for DNP/NMR at 600 MHz as a radiation source. Next, the operation mode switched from pulsed mode to CW mode. Output powers just after the output window for all of observed radiation peaks are 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 their application to many new

Table 1 Operation parameters of Gyrotron FU CW II at the fundamentals (N=1). Here are the demonstrated 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, beam efficiency. m in %, measured frequency f_{meas} in GHz and corresponding cavity mode number m,n.

B_0,T	P,W	V_b,kV	μ,%	f_{meas},GHz	f_{cal},GHz	$TE_{m,n}$	N
3.86	130	9.74	5.1	107.48	108.10	1,2	1
4.84	210	9.68	6.8	134.95	138.84	2,2	1
5.10	95	9.68	3.1	141.28	142.79	0,2	1
5.83	100	9.72	3.7	161.34	162.27	3,2	1
5.95	-	9.10	-	326.52	328.60	2,5	2
5.99	-	9.10	-	329.02	331.07	0,5	2
6.19	158	9.69	5.3	171.73	172.79	1,3	1
6.47	-	9.10	-	259.03	362.10	1,6	2
6.56	-	9.10	-	372.45	374.60	6,4	2
6.74	126	9.71	4.5	186.65	187.87	4,2	1
6.9860	17.9	9.62	0.49	386.03	388.20	4,5	2
7.15	24	13.66	0.52	392.25	396.4	2,6	2
7.19	32	13.675	0.72	394.27	396.69	2,6	2
7.22	180	9.79	8.8	200.43	201.75	2,3	1
7.38	170	9.82	9.6	204.54	205.87	0,3	1
7.62	181	9.81	9.7	211.40	443.51 -	5,2	1
7.98	5.3	9.62	0.14	440.93	443.51	6,5	2

technologies in the 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. The gyrotron FU CW II operates in the CW mode in long term of around 45 minute. The stabilities of the output power and frequency are several percent and several tens kHz, respectively.

We have confirmed that the 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 around 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 designed frequency of the principal mode TE_{26}, that is, 394.6 GHz. The output power is higher 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. 4.

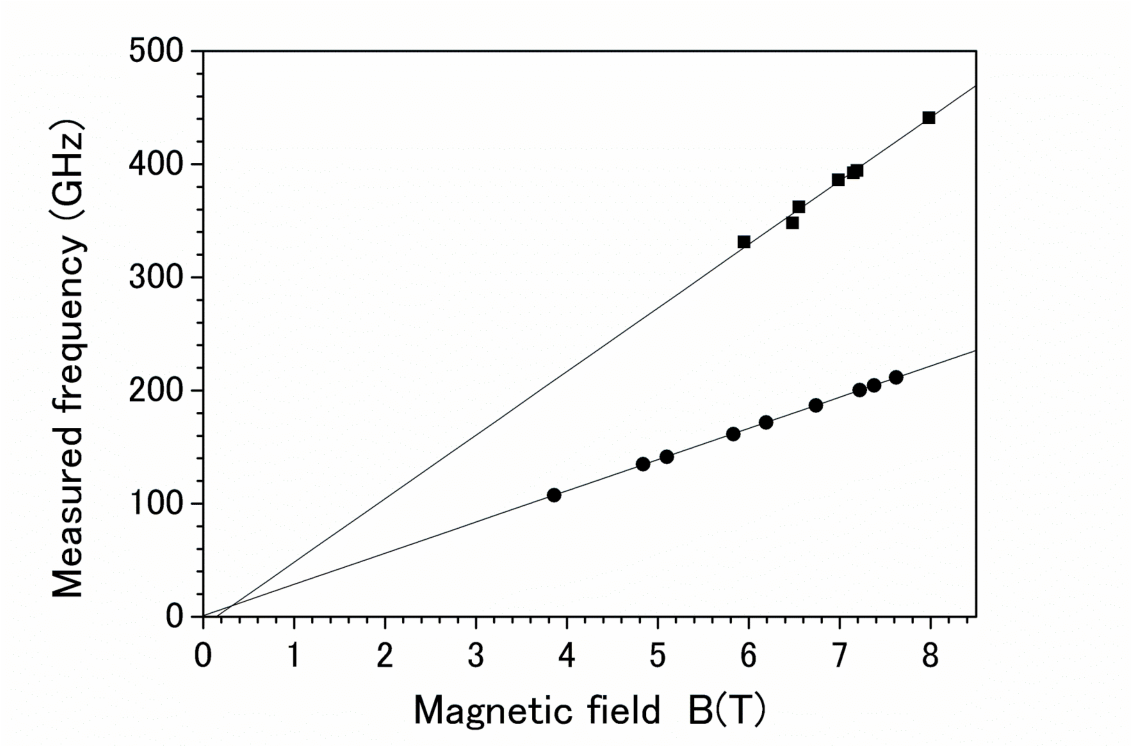


Fig. 4 All of observed frequencies as functions of magnetic field intensity.

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. 5. 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.

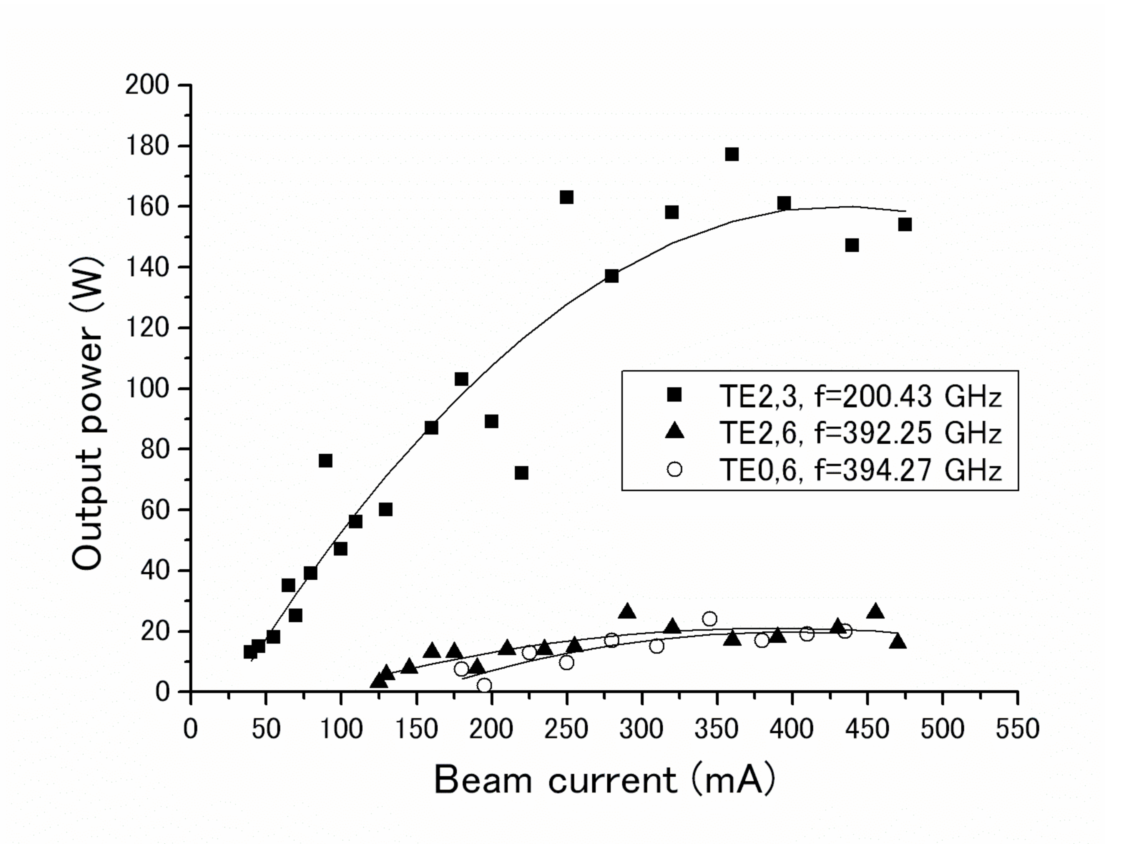


Fig. 5 Observed output power P for $TE_{2,3}$ mode at the fundamental, $TE_{2,6}$ and $TE_{0,6}$ modes at the second harmonics as functions of beam current I_b. Solid lines show the best fitting for three operation modes.

Fig. 6 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.

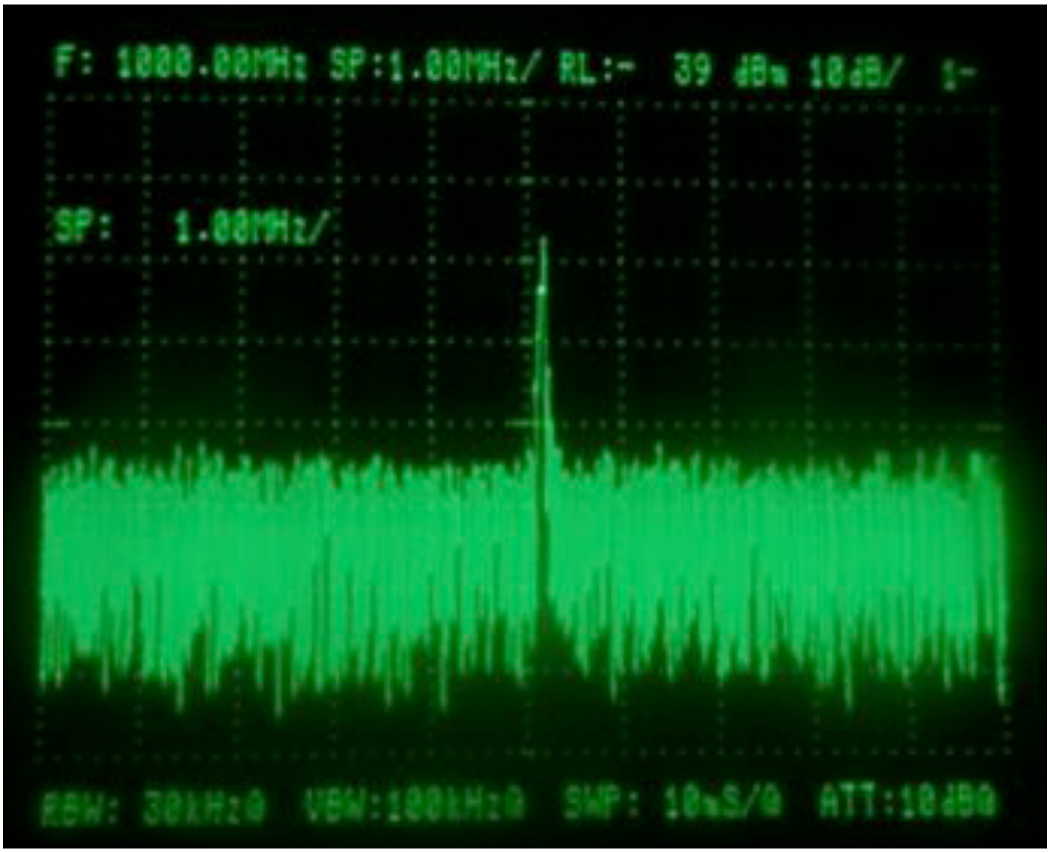


Fig.6 A frequency spectrum for TE_{06} mode operation at the second harmonic. Horizontal: 1 MHz/div. Vertical: log scale.

Table 3 Main parameters of Gyrotron FU CW III

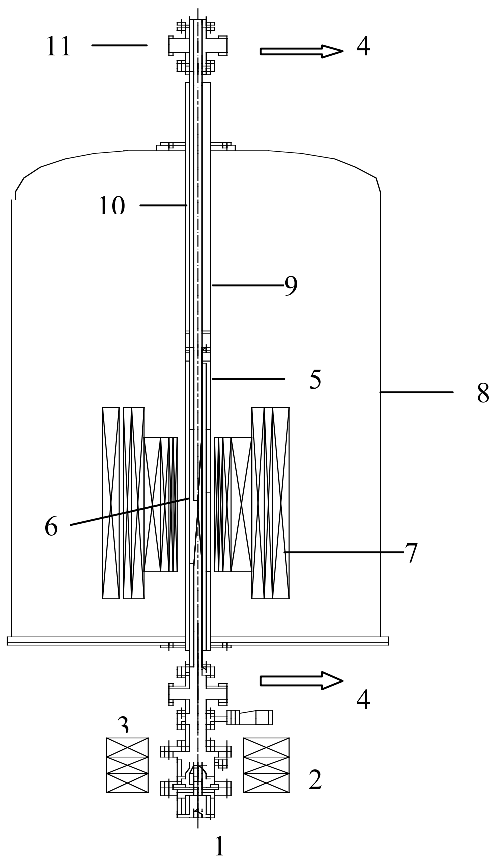
Total height (electron gun to the window):		2.4 m
SC magnetic	Maximum field intensity:	20 T
	The bore diameter:	50 mm
Cavity	radius:	1.95 mm
	length :	10 mm
	frequency:	1013.7 GHz
	Operating mode:	$TE_{4,12}$
	Q-factor :	23720
	Operating magnetic field:	19.1 T
Triode MIG:	Cathode radius:	4.5 mm
	Maximum cathode current:	1 A
	Cathode voltage:	30 kV
Gun coil	Maximum input current:	300 A
	Maximum field intensity:	0.183 T

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. 6, 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.

3. Gyrotron FU CW III

We have completed the design and initial testing of a new gyrotron, Gyrotron FU CW III[7)]. It consists of 20 T superconducting magnet and a demountable gyrotron tube. The diameter and length of the cavity are 3.9 mm and 10 mm, respectively. The designed operation frequency is increased up to 1.014 THz, which will be achieved by the second harmonic operation of $TE_{4,12}$ cavity mode at the magnetic field intensity of 19.1 T. An expected output power is higher than 0.1 kW. The design has been carried out according to the design of a pulsed gyrotron which achieved the first experiment of breakthrough of 1 THz. The main parameters of Gyrotron FU CW III are summarized in Table 3. It has been constructed and the operation test has already begun.

Fig. 7 shows a cross section of the Gyrotron FU CW III. Fig. 8 shows a typical result of radiation measurement as a function of magnetic field intensity B. There are many



1. Electron gun,
2. Gun coil,
3. Gate valve,
4. Tees to the pumping system,
5. Water jacket for cooling the cavity,
6. Cylindrical resonant cavity,
7. Superconducting magnet,
8. Cryostat,
9. Electron collector,
10. Water jacket for cooling the electron collector
11. Output window

Fig. 7 The cross-sectional view of the cylindrically symmetric 1 THz CW gyrotron tube. The gyrotron tube is approximately 2.5 m long and magnet bore diameter is 5 cm.

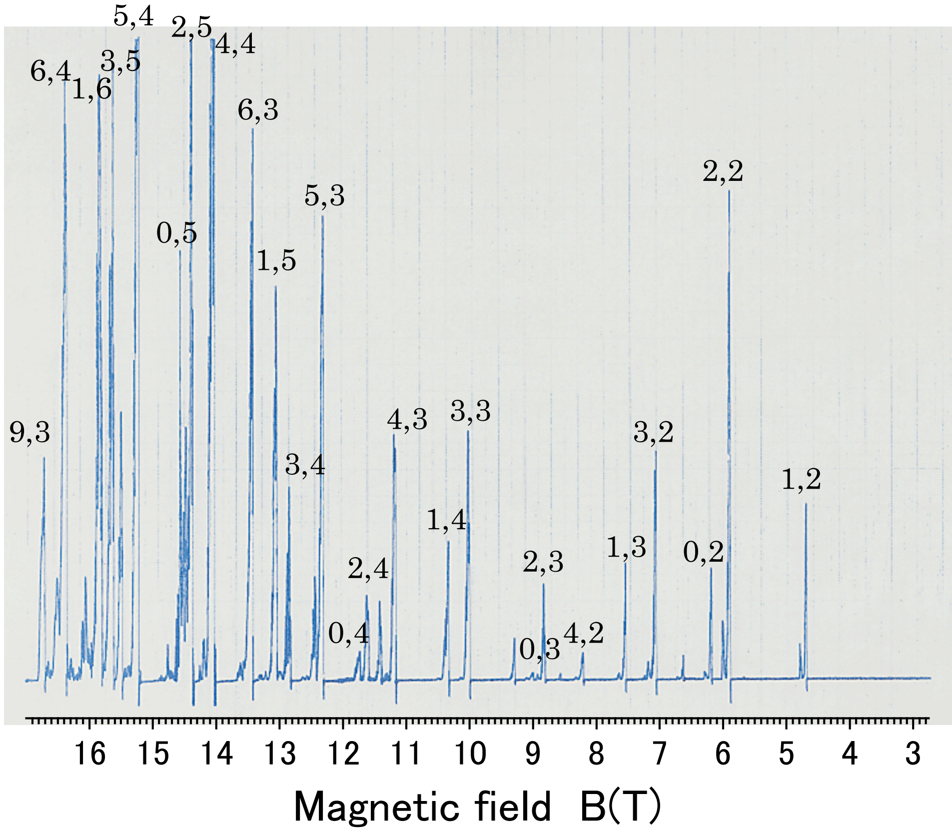


Fig. 8 Radiation power emitted from the Gyrotron FU CW III as a function of magnetic field intensity

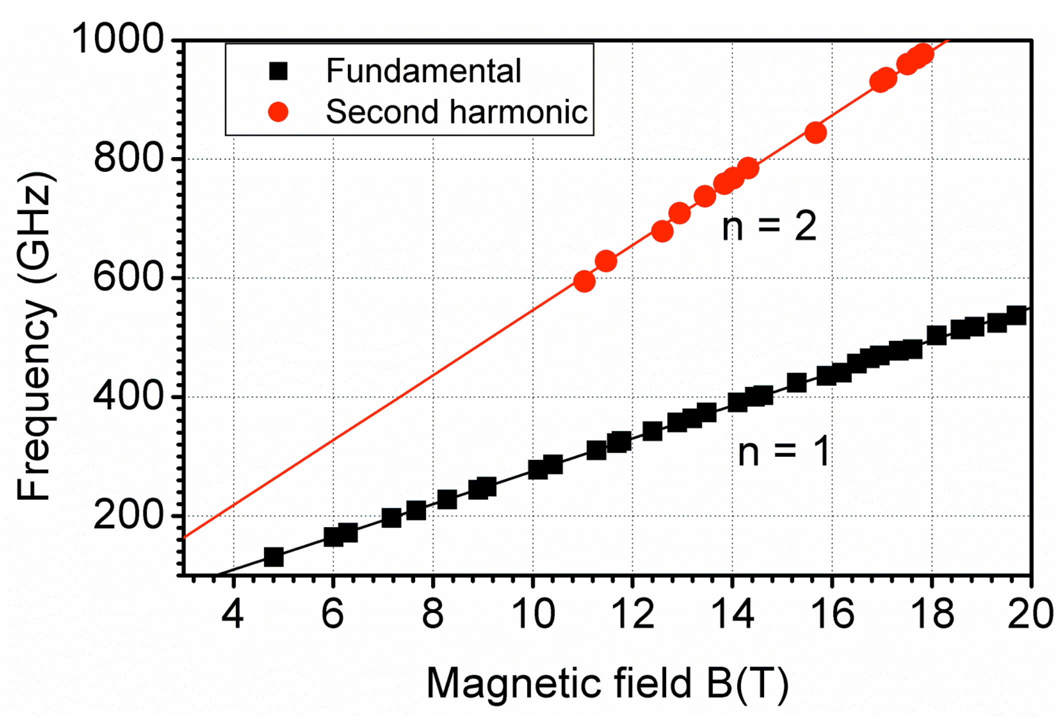


Fig. 9 All frequencies excited up to the present as functions of magnetic field B.

radiation peaks corresponding to cavity modes. Almost all cavity modes are excited in the fundamental operations. A similar measurement for the second harmonic operations has also been carried out successfully.

Fig. 9 summarizes the results. All frequencies expected from the excited cavity modes are plotted as functions of B. The maximum frequency achieved up to the present by the second harmonic operation is 980 GHz in the field range below 18 T. A frequency step tuneability is also achieved by Gyrotron FU CW III. We hope to increase the field intensity up to 20 T for the second harmonic operation to achieve the operation beyond 1 THz.

Table 4 Measured frequencies f_{meas}, some of output powers P_{meas}, mode numbers of cavity m,n and harmonic numbers N are compared with the frequencies of ESR f_{ESR} corresponding to the frequencies of NMR f_{NMR}. The gyrotron operates in the pulse mode.

f_{NMR}, MHz	f_{ESR}, GHz	f_{meas}, GHz	$P_{meas.}$ W	Modes m,n	N (Gyrotron)
600	394.6	394.3 390.9	32 178	0,6 4,4	2 (FU CW II) 1(FU CW III)
700	460.4	456.2	220	6,4	1(FU CW III)
800	526.2	569.5	/	7,5	2(FU CW III)
900	591.9	616.4	/	6,6	2(FU CW III)
1000	657.7	672.0	/	1,9	2(FU CW III)

The operation mode is pulsed. Typical repetition rate and duty ratio are 1 Hz and 20 percent. On the basis of the results of operation test shown in Figs. 8 and 9, we can consider a possibility to apply our high frequency gyrotrons to higher frequency DNP/NMR. Table 4 shows frequencies f_{ESR} required for DNP/NMR and measured frequencies near the required ones which Gyrotron FU CW II and III have achieved. In addition, some of the measured output powers P_{meas}, cavity modes m,n and harmonic number N are indicated. If the optimum design of cavity will is carried out for each frequency of NMR, Gyrotron FU CW III can be used for higher frequency DNP/NMR. The frequency will be increased up to 1 GHz.

4. Summary

The THz CW Gyrotron Series in FIR FU are being developed successfully. Developed Gyrotron FU CW II is being applied to high power DNP/NMR at 600 MHz. The frequency is 394.3 GHz and the output power is higher than 30 W in CW operation at the second harmonic. Gyrotron FU CW III achieved the maximum frequency of 980 GHz. We hope to increase the frequency beyond 1 THz at CW operation soon by increasing the fields intensity up to 20 T. Obtained results of operation tests shown in the previous section demonstrate a possibility to apply the gyrotron to higher frequency DNP/NMR up to 1 GHz.

Acknowledgements
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