THz Gyrotrons - FU CW Series for high power THz technologies

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Development and application of high power THz radiation sources – Gyrotron FU CW Series are presented. All of the gyrotrons included in the series operate in CW or long pulse modes. The series is now being developed and applied to high power THz technologies, for example, plasma diagnostics, DNP-NMR for protein research, etc. At the present, the series consists of four gyrotrons, Gyrotron FU CW I, II III and IV. Now, we are developing Gyrotron FU CW V for application to accurate measurement of energy level of positronium. Such activities concerning with development and applications of Gyrotron FU CW Series are presented.

Keywords: Gyrotron, High power THz source, Terahertz, CW operation, DNP-NMR,

1. Introduction

Our previous Gyrotron FU Series has already achieved high frequency operation up to 0.89 THz by using a 17 T superconducting magnet and the second harmonic operation.[1)] Recently, a gyrotron in FIR FU with a 21.5 T pulse magnet succeeded in the first experiment on the breakthrough of 1 THz. [2)]

For convenience of the application to high power THz technologies, CW gyrotrons (Gyrotron FU CW Series) is being developed. Gyrotron FU CW I has been developed and succeeded in the CW operation at 300 GHz under high power of 2.3 kW. The next gyrotron, Gyrotrons FU CW II and III have also been developed. The parameters are as follows, 394 GHz, 100 W for FU CW II[3)] and 1.08 THz 100 W for FU CW III. Both gyrotrons operate in CW or long pulse mode. Gyrotron FU CW IV is a frequency continuously tunable gyrotron.

2 Gyrotron FU CW Series

2-1 Gyrotron FU CW I

In FIR FU, we are developing high frequency CW gyrotrons named Gyrotron FU CW Series as high power THz radiation sources. We have already developed Gyrotron FU CW I. The frequency is 300 GHz, output power 2.3 kW, the operation is complete CW.[3)] It is now being applied for material processing system.

2-2 Gyrotron FU CW II

Just, we have finished the construction of a next CW gyrotron, Gyrotron FU CW II and begun the operation test. Fig. 1 shows a cross section of the gyrotron and Fig. 2 the side view.

The gyrotron consists of a 12 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 $TE_{2,6}$ cavity mode.

After completing the operation test, the gyrotron will be used for enhancement of NMR sensitivity by use of dynamic nuclear polarization (DNP). 394.6 GHz is corresponding to ESR frequency at the field intensity of around 7.1 T. The frequency of proton NMR at the field is 600 MHz.

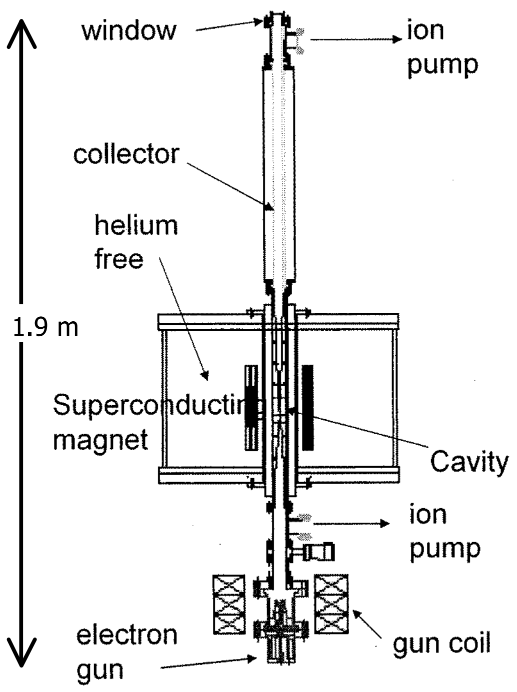

Fig. 1 The cross section of Gyrotron FU CW II

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Fig.2 Side-view of Gyrotron FU CW II

We have already succeeded to operate the gyrotron at many fundamental and second harmonic resonances. Cavity modes corresponding to almost all radiations resulting from fundamental and second harmonic operations are identified. We have found the operation at the $TE_{0,6}$ cavity mode whose frequency measured by a heterodyn detection system is 394.4 GHz. It is a little bit lower frequency than the designed frequency. [3)]

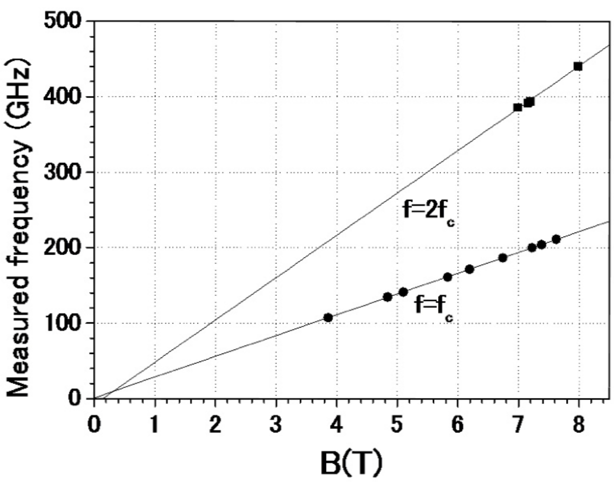

Fig. 3 All frequencies measured by a heterodyn detection system as functions of magnetic field intensity.

Fig. 3 shows all of frequencies observed up to the present as functions of magnetic field intensity. Measured frequencies are distributed in the range from 61 GHz to 209 GHz in the case of fundamental operations, while from 212 to 439 GHz in the case of second harmonic operations. Now, we are measuring the output power of Gyrotron FU CW II. Typically, the output power is several hundred watt for fundamental operations and several tens watt for the second harmonic operations.

3-3 Gyrotron FU CW III

The third gyrotron, Gyrotron FU CW III with a 20 T superconducting magnet [4)] has already been constructed and operated. In Table 1, main parameters of the gyrotron are shown. The gyrotron is optimized for the second harmonic operation of $TE_{4,12}$ at the frequency of 1013.7 GHz. The operation mode is complete CW. This gyrotron has achieved the breakthrough of 1 THz in CW operation. In addition, many other cavity modes were excited by adjusting the field intensity at the optimum value for each cavity mode. As the results, The gyrotron has achieved frequency step tuneability in wide range covering sub-THz to THz frequency region.

Table 1 Specification of Gyrotron FU CW III

Total height from electron gun to the window: 2.4 m
Superconducting magnet :
Maximum magnetic field : 20 T
Inner bore diameter: 50 mm
Cavity :
Radius: 1.95 mm, Length : 10 mm,
Frequency : 1013.7 GHz at the second harmonic,
Cavity mode : $TE_{4,12}$, Q-factor : 23720
Operation mode: Complete CW
Operating magnetic field: 19.1 T for $TE_{4,12}$
Triode-type electron gun:
Cathode radius: 4.5 mm,
Maximum cathode current: 1 A,
Maximum cathode voltage: 30 kV
Gun coil:
Maximum input current: 300 A,
Maximum magnetic field: 0.183 T
Pumping bores:
1.Near the electron gun,
2.Near the output window.
Water cooling jackets are installed at a cavity and a collector regions.

Fig. 4 and Fig. 5 show the cross section and a photo of Gyrotron FU CW III. The operation test has already been carried out successfully. Fig. 6 shows output frequencies as function of magnetic field intensity.

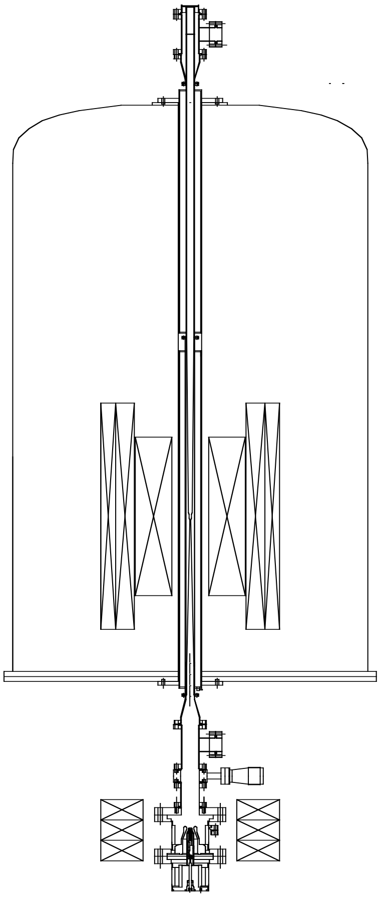

Fig. 4 The cross section of Gyrotron FU CW III

Fig.5 Photo of Gyrotron FU CW III

Fundamental operations are measured just after the output window and second harmonic operations through high pass filters. Excited cavity modes for almost all radiation peaks are identified.

Fig. 7 shows measurement result of second harmonic radiations after high pass filters as function of magnetic field intensity. Four high pass filters for corresponding frequency ranges are used to remove the fundamental radiations. The highest frequency is around 1.08 THz

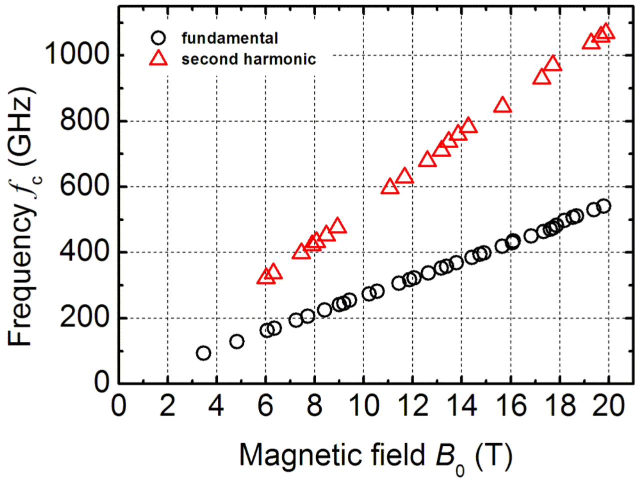

Fig. 6 Measured frequencies as functions of magnetic

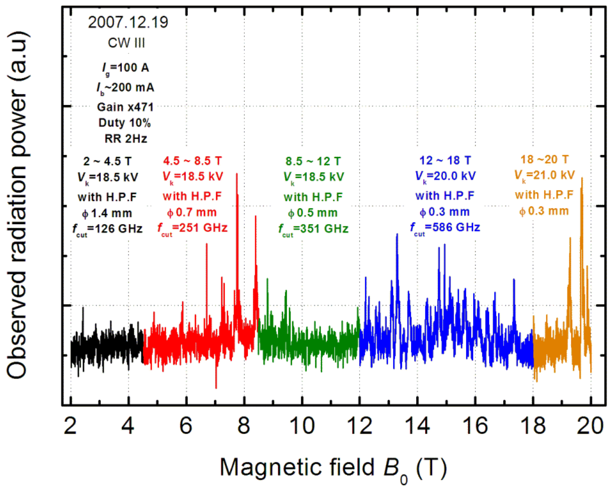

Fig. 7 Radiation power measured after high pass filters as a function of magnetic field intensity

near the field intensity of 20 T. Frequency step tuneability covering the range from 0.1 to 1.08 THz. The measurement of output power is carried out by a water load. It depends on the cavity modes. Typically, it was several hundred watt at the fundamental operations and several tens watt at the second harmonic operations

3-4 Gyrotron FU CW IV

The latest gyrotron included in Gyrotron FU CW Series, Gyrotron FU CW IV consists of a 10 T liquid helium free superconducting magnet, a demountable gyrotron tube, additional copper coils in a gun region and several power supplies for magnets, electron gun etc. Fig. 8 shows the side-view of the gyrotron. It was designed as a radiation source for sensitivity enhancement of 200 MHz proton NMR by use of DNP. The frequency of ESR corresponding to 200 MHz proton NMR is around 131.5 GHz. The most important advantage of Gyrotron FU CW IV is a frequency continuously tuneablity near 131.5 GHz.

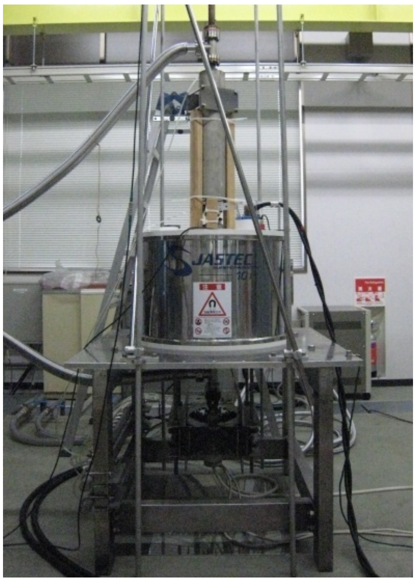

Fig. 8 A side-view of Gyrotron FU CW IV.

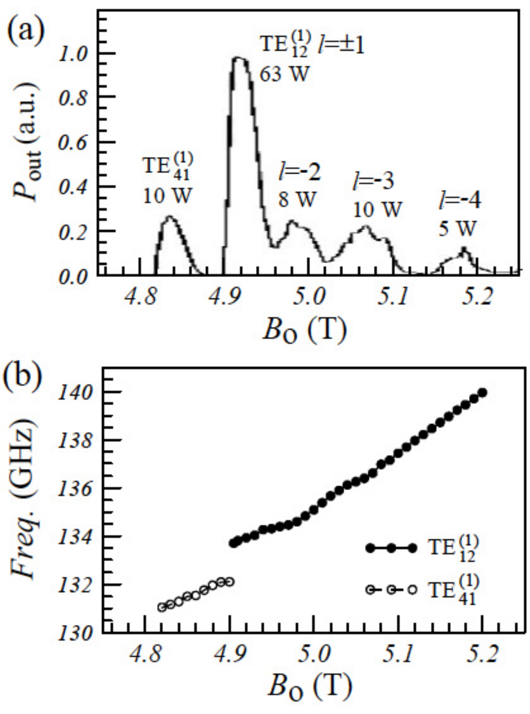

Fig. 9 Measurement results of output power (a) and output frequecies(b).

Fig. 9 shows measurement results of frequency continuous tenability and corresponding output powers. Frequency is varied around 4.3 percent (6 GHz around 140 GHz) and output power was also varied from several watt to 60 watt. By using $TE_{12\ell}$ (ℓ =1, 2, 3, …) modes and backward wave interaction between an electron beam and backward components of cavity modes $TE_{12\ell}$, the frequency tenability is achieved.

4. Summary

Three CW gyrotrons, Gyrotron FU CW I, II and III operating in sub-THz to THz region are being developed. Operation test of these gyrotrons have already carried out. Gyrotron FU CW I is being used for material processing. Gyrotron FU CW II has been installed on a 600 MHz proton-NMR device at Institute of Protein Research, Osaka University for sensitivity enhancement of NMR spectroscopy by using Dynamic Nuclear Polarization (DNP). Gyrotron FU CW III will be used for development of high power THz technologies, for example, DNP/NMR spectroscopy, X-ray detected magnetic resonance (XDMR) experiment, accurate measurement of energy levels of positronium, high frequency ESR echo measurement, plasma scattering measurement etc.

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