LONG PULSE OPERATION OF THz GYROTRON WITH A PULSE MAGNET

研究報告 1

LONG PULSE OPERATION OF THz GYROTRON WITH A PULSE MAGNET

T. Idehara, T. Saito, H. Mori, H. Tsuchiya, La Agusu and S. Mitsudo

Research Center for Development of Far Infrared Region, University of Fukui (FIR FU)
Bunkyo 3-9-1, Fukui-shi 910-8507, Japan

Abstract

Long pulse operation up to 1 msec of a high frequency gyrotron with a pulse magnet has been successfully carried out in a frequency range including 1 THz. In the trial, the timing of an electron beam pulse injection is adjusted at the top of the magnetic field pulse, where the variation of field intensity is negligible. The operation cavity modes are $TE_{10,8}$ and $TE_{4,12}$ at the second harmonics. Corresponding frequency for $TE_{4,12}$ mode is 1,013 GHz. Additional several features of radiation measurement results of the gyrotron are described and brief considerations are presented.

1. Introduction

In Research Center for Development of Far Infrared Region, University of Fukui (FIR FU) , we have developed high frequency gyrotrons covering a frequency range of sub-THz during around three decades by using high field superconducting magnets and high harmonic operations. [1)-5)] The long-term world record of high frequency operation of gyrotron at 889 GHz was achieved in 1994 by our Gyrotron FU IVA. Similar studies are being advanced in MIT[6)], University of Sydney[7),8)] and IAP-RAS[9)]. Recently, we have succeeded to achieve a frequency breakthrough of 1 THz by a second harmonic gyrotron with a pulse magnet[10)]. This is the first challenge to gyrotron operation at 1 THz.

Development of high power THz radiation sources are quite important for development of high power THz technologies, for example, plasma diagnostics[11),12)], enhancement of NMR sensitivity using dynamic nuclear polarization (DNP)[13)-15)], high frequency ESR spectroscopy[16)] in nonlinear regime, communication in the frequency range of THz. Among many radiation sources, a gyrotron is one of most appropriate ones for such a objectives, because of high efficiency even in high frequency and high harmonic[4)], stability of frequency and amplitude[17)] and possibility of long pulse or CW operation in long time.

For application to such new high-power technologies in THz region mentioned above, we have already begun the development of CW gyrotrons, named "Gyrotron FU CW Series". Development of the first gyrotron, Gyrotron FU CW I was completed and CW output of 1.75 kW was obtained at the frequency of 300 GHz. The cavity mode is $TE_{22,8}$ at the fundamental operation. The second gyrotron, Gyrotron FU CW II[14),15)] was constrsucted and preliminary operation results have been obtained. The designed mode is $TE_{2,6}$ mode at the frequency of 394.6 GHz. The operation is at the second harmonic. It will be used for sensitivity enhancement of 600 MHz proton NMR by use of DNP method. In experiment, we obtained the second harmonic operation of TE_{06} cavity mode at the frequency of 394.3 GHz, because of the fabrication error of cavity radius. The radius of the real cavity is larger than that of designed cavity by about 0.57 percent.

Design of the third gyrotron, Gyrotron GU CW III [18)] was completed and the construction was almost finished. The operation test is starting soon. The frequency range will cover in sub-THz to THz by the fundamental and the second harmonic operations. The intensity of magnetic field generated by a superconducting magnet is increased up to 20 T.

In this paper, is described long pulse operations at the second harmonic achieved by a THz gyrotron with a pulse magnet. In addition, several features of radiation measurement results of the gyrotron are described and brief considerations for the results are presented. The results described in the previous paper[10)] and this paper are quite important for us, because design of our next principal device, Gyrotron FU CW III, was carried out on the basis of successful measurement results of the THz gyrotron with a pulse magnet. Hopefully, the Gyrotron FU CW III will be used in future to open the high power THz technologies.

In section 2, an experimental setup and procedure are described. In section 3, simulation results are described. In section 4, experimental results are demonstrated and considerations for the results are presented and In section 5, the contents of the paper are summarized.

2. Experimental setup and procedures

As already described in the previous paper[10], the THz gyrotron consists of a demountable gyrotron tube with high Q value for high frequency cavity modes, an ice-protecting pulse magnet whose maximum field intensity is 20.5 T. Fig. 1 shows the block diagram of the whole system of a THz gyrotron.

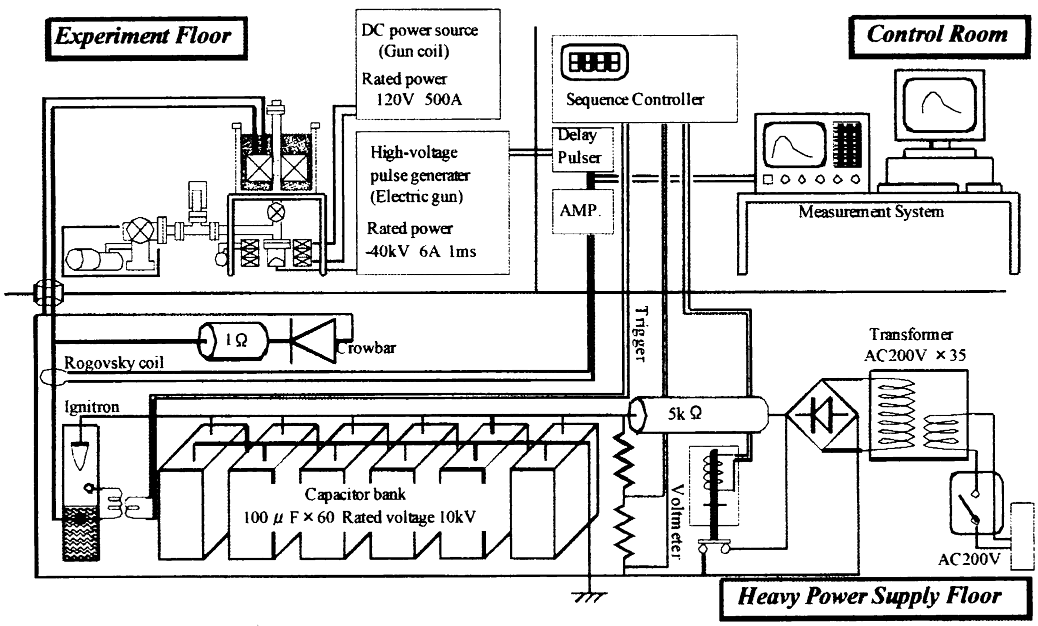

Fig. 1 A block diagram of the whole system of a THz gyrotron with a pulse magnet. 300 kJ condenser bank for the pulse magnet, power supplies for a triode magnetron injection gun and gun coils and a controlling system for the whole gyrotron system.

A so-called "ice-protecting pulse magnet" is installed on the second floor. It is a simple solenoid coil whose length, inner diameter and outer diameter are 112 mm, 43 mm and 129.4 mm, respectively. Copper wire is wound in 299 turns. The coil is inserted in stainless steel cylinder whose inner diameter and thickness are 170.3 mm and 22.4 mm, respectively. Water with alumina powder surrounds the coil and fills the clearance between the coil and a stainless steel cylinder. The whole magnet system is installed in a cryostat and cooled down by liquid nitrogen. Then, water with alumina powder is frozen and fixes the solenoid coil tightly in order to protect the coil from expanding in radial direction.

The pulse magnet is operated by using a capacitor bank installed on the first floor. The total capacitance is 6 mF and maximum biased voltage is 10 kV. Therefore, the maximum stored energy is 300 kJ. It is discharged through an ignitron and applied to the pulse magnet. The field intensity is increased up to 20.5 T and the pulse width is several millisecond, usually, 3 to 5 ms. In addition to the pulse magnet, three water-cooled copper coils are installed in the gun region to control parameters of electron beam, such as an injection radius in a cavity and a pitch factor of beam electrons.

The pulse width of electron beam injection is typically 1 ms. The gyrotron operates in quite short pulse only at the moment when the field intensity satisfies the resonance condition at the fundamental or the second harmonics. The timing of the injection of the electron beam pulse is controlled by the controlling system installed on the second floor. When we try the long pulse operation of the gyrotron, we should control the timing so that the electron beam pulse is injected at the top of magnetic field pulse where the field intensity is almost constant. Then, if the field intensity at the top is adjusted at the resonance point by adjusting the stored energy of the capacitor bank, the resonance condition is kept in the whole injection pulse of electron beam. This means that such a careful setting of the operation conditions makes a long pulse operation of the gyrotron possible.

A demountable gyrotron tube is placed on the axis of the magnet. All of the components of the gyrotron tube, for example, an electron gun, a resonant cavity, an output window and a transmission waveguide from the cavity to the output window can be replaced and renewed, if it is needed for optimization of the gyrotron operation. A vacuum layer of the cryostat is expanded to the inside of the gyrotron tube. Usually, the pressure in the tube is less than 10^{-7} Torr.

We are using a triode magnetron injection gun in order to control the beam parameters for modulation of amplitude and frequency[19]. Mirror ratio defined as B_c/B_g is varied from 84 to 127, where B_c and B_g are magnetic field intensities at cavity region and gun region, respectively.

A cavity has a simple cylindrical shape whose inner diameter and length are 3.9 mm and 10 mm, respectively. As described already[10], the gyrotron has achieved the breakthrough of 1 THz by the second harmonic operation of $TE_{4,12}$ cavity mode. The corresponding frequency is 1.013 THz. The field intensity for the operation is 19.1 T. Such a high field was realized by the ice-protecting pulse magnet. One of cavity modes for which we tried long pulse or CW operations is the same mode, $TE_{4,12}$.

The output window consists of sapphire disk whose diameter and thickness are 33 mm and 2.5 mm, respectively. An output power from the cavity is transmitted through the circular waveguide (the inner diameter is 28 mm) and the window, and then comes out to the external waveguide whose inner diameter is 28 mm.

3. Simulation results

First of all, we tried to estimate the field intensity profile in a cavity region, which is generated by the pulse magnet. The effect of eddy current induced on the cavity wall is taken into account and time evolution of field intensity at each point in a region including a cavity is estimated. From the results, the field profile in a cavity region can be constructed with the time as a parameter. The eddy current effect makes the field profile unsymmetric. The uniformity in the cavity region is kept at around 1 percent, which is enough for stable operation of the gyrotron. The time evolution of field intensity at the center of cavity is observed with biased voltage of capacitor bank as a parameter. The maximum field intensity is increased up to 20.5 T with biased voltage of a capacitor bank increased.

Next, simulations for trajectories of beam electrons are carried out for a used triode

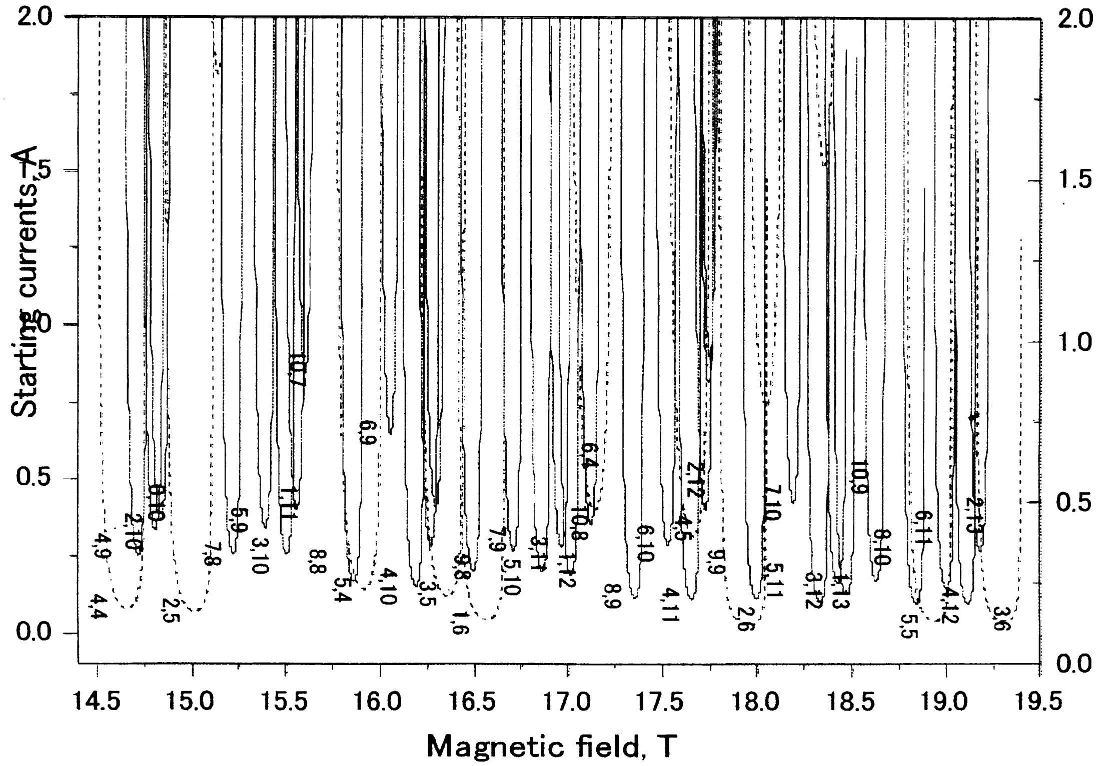

Fig. 2 Starting current (in A) of each cavity mode $TE_{m,n}$ operation at both fundamental (Broken line) and the second harmonic resonance (Solid lines). Mode numbers m and n are mentioned near calculated lines. Mode numbers m,n are indicated near corresponding calculation curves.

magnetron injection gun and field configuration. The result shows that almost all electrons penetrate through the cavity region toward the collector. Obtained beam electron parameters are as follows: the pitch factor is around 1.2 and the spread of perpendicular velocity 5 percent, under the assumption that the beam electron energy is

30 keV and beam current 150 mA..

Finally, we tried the estimation of starting current of each cavity mode operation at both fundamental and the second harmonic resonances. The results are shown in Fig. 2. There are many possible cavity modes excited in the beam current range below 150 mA in both fundamentals and the second harmonics.

4. Experimental results and considerations

4-1 Long pulse operation up to 1 ms in sub-THz to THz frequency range

We tried a long pulse operation by use of second harmonic operation of $TE_{4,12}$ cavity mode which is the same mode used for the first experiment[10] of the breakthrough of 1 THz. Fig. 3 shows a typical experimental result.

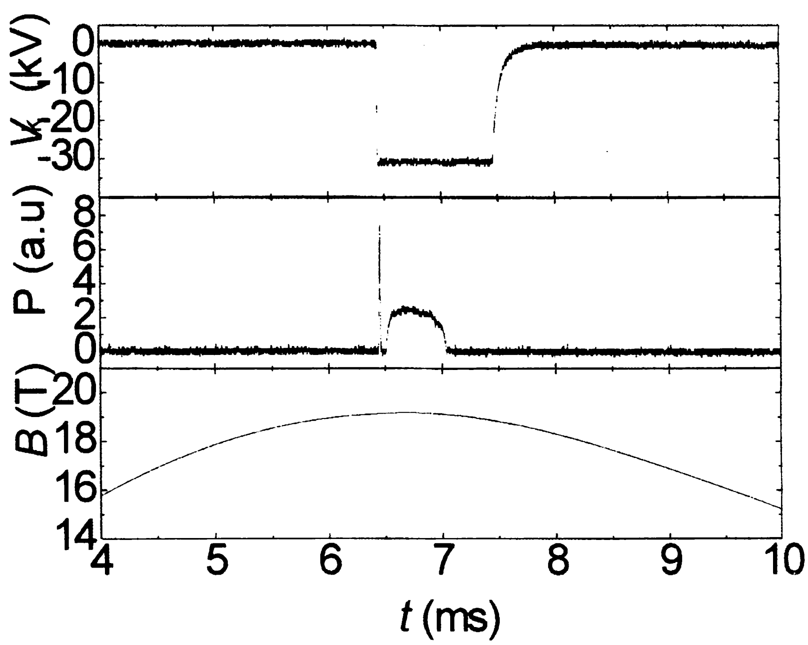

Fig.3 A typical result for long pulse operation of $TE_{4,12}$ cavity mode at the second harmonic. Upper trace: High voltage pulse applied to gun cathode, Middle trace: Output radiation power measured after a high pass filter with narrow circular waveguide whose inner diameter is 0.3 mm. Lower trace: Time variation of applied pulse magnet intensity.

As seen in the upper trace of the figure, an electron beam pulse is injected near the top of the field pulse (a lower trace) generated by a pulse magnet. The field intensity at the top is optimized at aroung 19.1 T for second harmonic operation of $TE_{4,12}$ cavity mode by adjusting precisely the stored energy of the condensor bank. The output radiation was measured after a high pass-filter with narrow circular waveguide whose inner diameter is 0.3 mm. We used an InSb hot electron dectector cooled by liquid helium for the measurement. The cutoff frequency of the filter is

586 GHz. Therefore, radiation resulting from the fundamental operations is removed from the measurement. The result is demonstrated in the middle trace. As seen in the trace, the radiation pulse width of around 0.5 ms is observed. The width became much wider comparing with the previous results where it is less than 0.1 ms[10]. It results from the second harmonic operation of $TE_{4,12}$ cavity mode. The expected frequency is 1,013 GHz. This frequency could be measured by heterodyne detection system with a spectrum analyzer.

In Fig. 4, another example for long pulse operation is demonstrated. In this case, the operation cavity mode is $TE_{10,8}$ and the operation is at the secod harmonics. It is seen that the pulse width of the radiation power is around 1 ms. The expected frequency is xxx GHz. As shown in both Figs. 3 and 4, long pulse operations near 1 ms were achieved. Such THz radiations with long pulse is useful for its application to high power THz technologies.

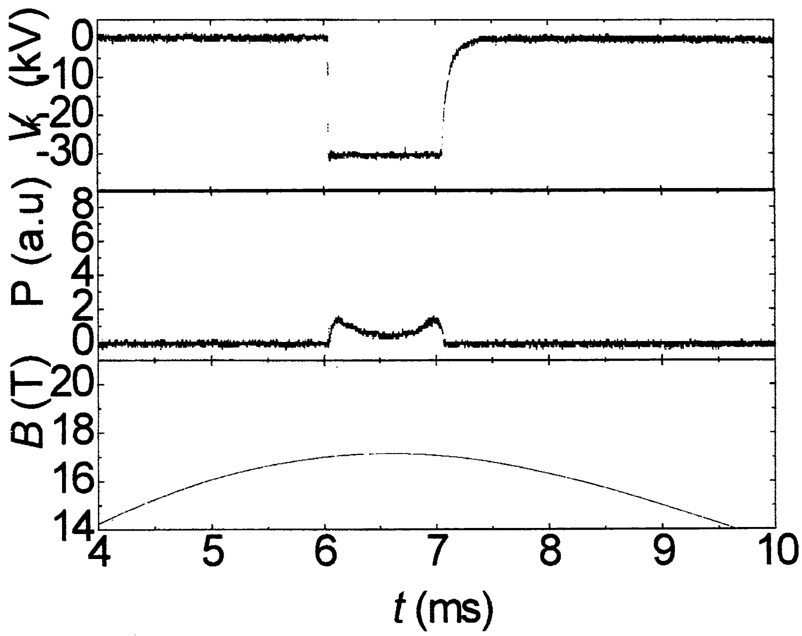

Fig.4 Another typical result for long pulse operation of $TE_{10,8}$ cavity mode at the second harmonic. Upper trace: High voltage pulse applied to gun cathode, Middle trace: Output radiation power measured after a high pass filter with narrow circular waveguide whose inner diameter is 0.3 mm. Lower trace: Time variation of applied pulse magnet intensity.

3-2 Some additional results of radiation measurement on the THz gyrotron

Following long pulse operations of the THz gyrotron, we continued to measure many operation modes. Here, we are describing some additional features of the radiation measurement on the THz gyrotron.

Fig. 5 shows measurement results when the timing for injection of electron beam pulse is adjusted far from the top of the magnetic field pulse. As seen in the upper figure, the magnetic field intensity (lower trace) varries significantly during pulse duration of high voltge (upper trace) applied to the gun cathode. Therefore, raditation peaks coming from the excitation of several cavity modes appear at the corresponding magnetic field

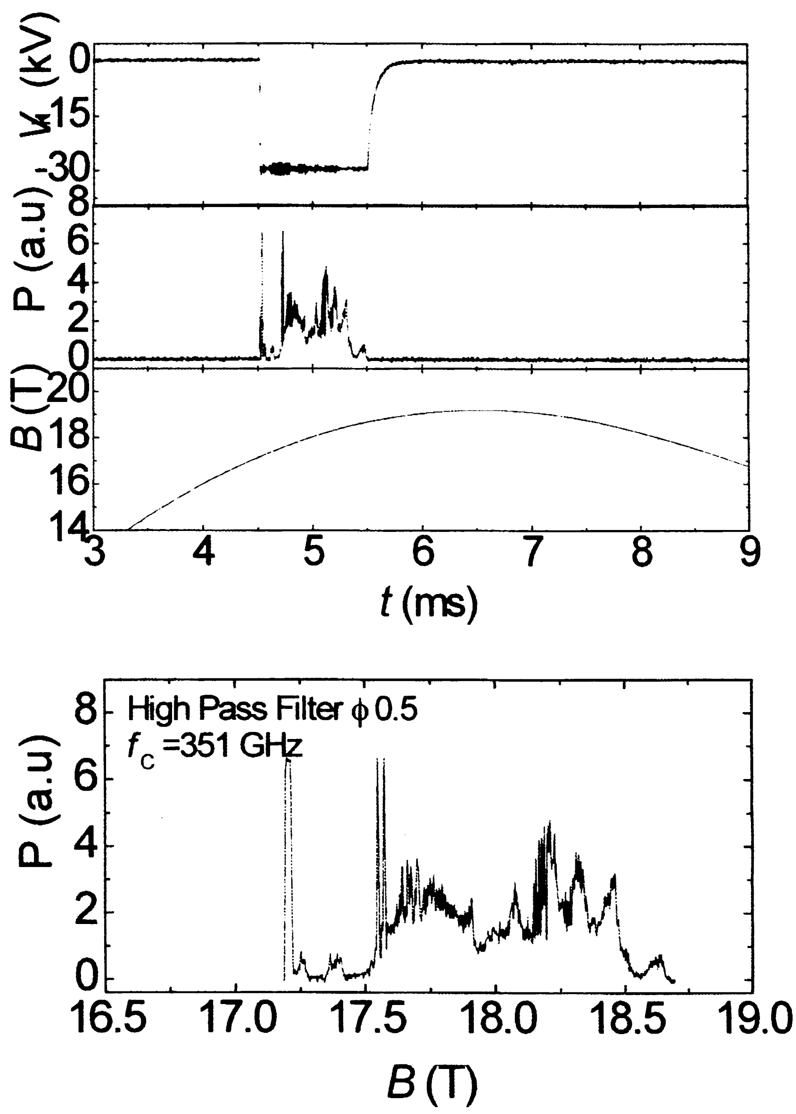

Fig. 5 Upper figure: Time evolution of high voltage pulse applied the gun cathode, Radiation power measured just above the output window by a InSb hot electron detector and magnetic field intensity generated by a pulse magnet. Lower figure: Radiation power measured just above the output window by a InSb hot electron detector as a function of magnetic field intensity. A high pass filter with a circular waveguide whose diameter is 0.5 mm is used. The cutoff frequency is 351 GHz.

intensities, as seen in the middle trace. The lower figure summarizes the measured radiation power as a function of the field intensity. The measurement is carried out after a high pass filter with a circular waveguide whose diameter is 0.5 mm. In the field intensity range from 17 T to 19T, both fundamental and second harmonic are included in the trace shown in the lower figure, because the cut-off frequency of the high pass filter is 351 GHz.

Many similar measurements have been carried out in the different ranges of the magnetic field intensity which totally cover the whole range from 14 T to 19.5 T. The results are summarized in Fig. 6 as a function of magnetic field intensity.

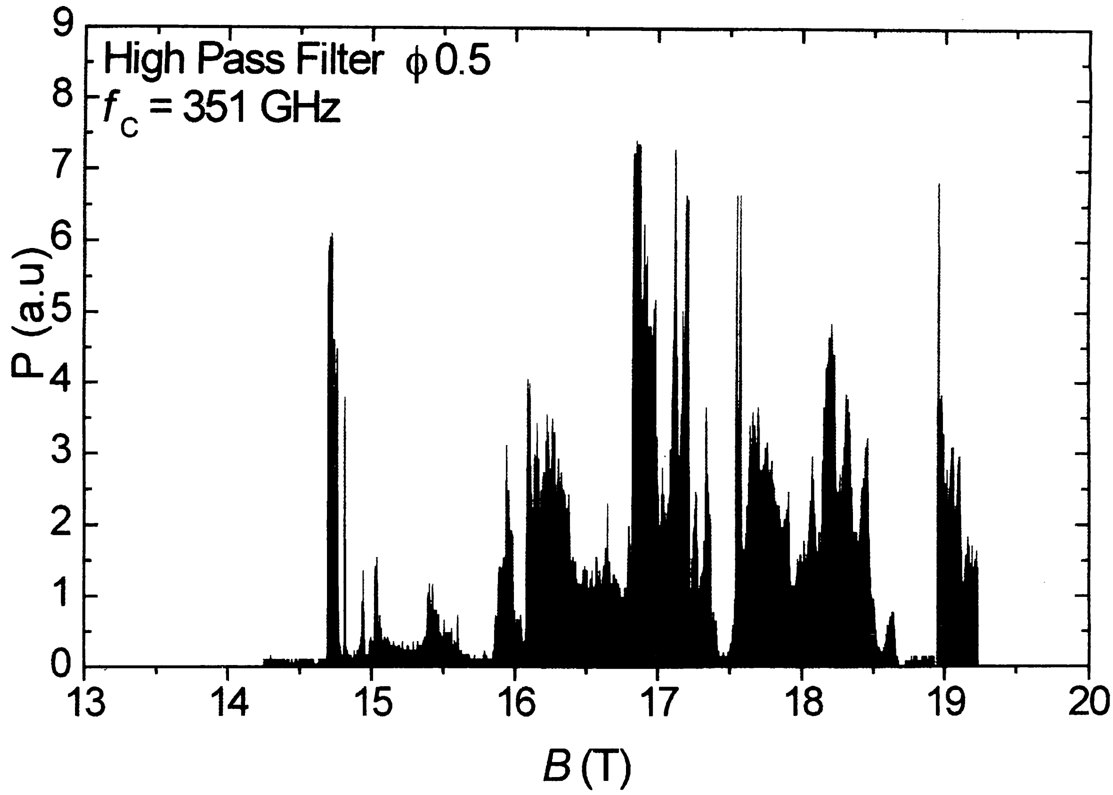

Fig. 6. Radiation power measured after a high pass filter with a circular waveguide whose dimeter is 0.5 mm are summarized as a function of magnetic field intensity.

Cavity modes corresponding to principal peaks of raditation power are identified from the estimated frequencies.

The similar measurements of radiation power for excitation of second harmonic operations were also carried out by using another high-pass filter with a circular waveguide whose dismeter is 0.3 mm. The cutoff frequency is 586 GHz. Therefore, in the range of field intensity from around 11 T to 20.5 T, the fundamental radiation peaks are removed and only second harmonics remain in the trace of radiation power. Fig. 7 summarizes such measurements and demonstrates the measured radiation power as a function of the field intensity. As seen in the figure, the radiation peaks are not so many, because some second harmonic operations compete with neighber fundamentals with much higher power and never appear. The radiation peaks appearing in the figure result from single mode operations of second harmonics without mode competitions with any fundeamental modes. The half value widths of radiation peaks observed in the figure are much narrower than those for the fundamenrtal case shown in Fig. 6. The reason for this feature maybe as follows,

1) Q-value of the cavity for second harmonic operation is higher than that for fundamentals. High Q value makes the half value width narrower.
2) If there are both fundamental and second harmonic modes excited at almost same field intensity, the frequency of the latter is almost two times of the former. This means that the field intensity width corresponding to a certain frequency width in the second harmonic is a half of that in the fundamental for the same frequency width.

This feature of narrower width for second harmonic is also seen in the calculation results for starting current shown in Fig.2.

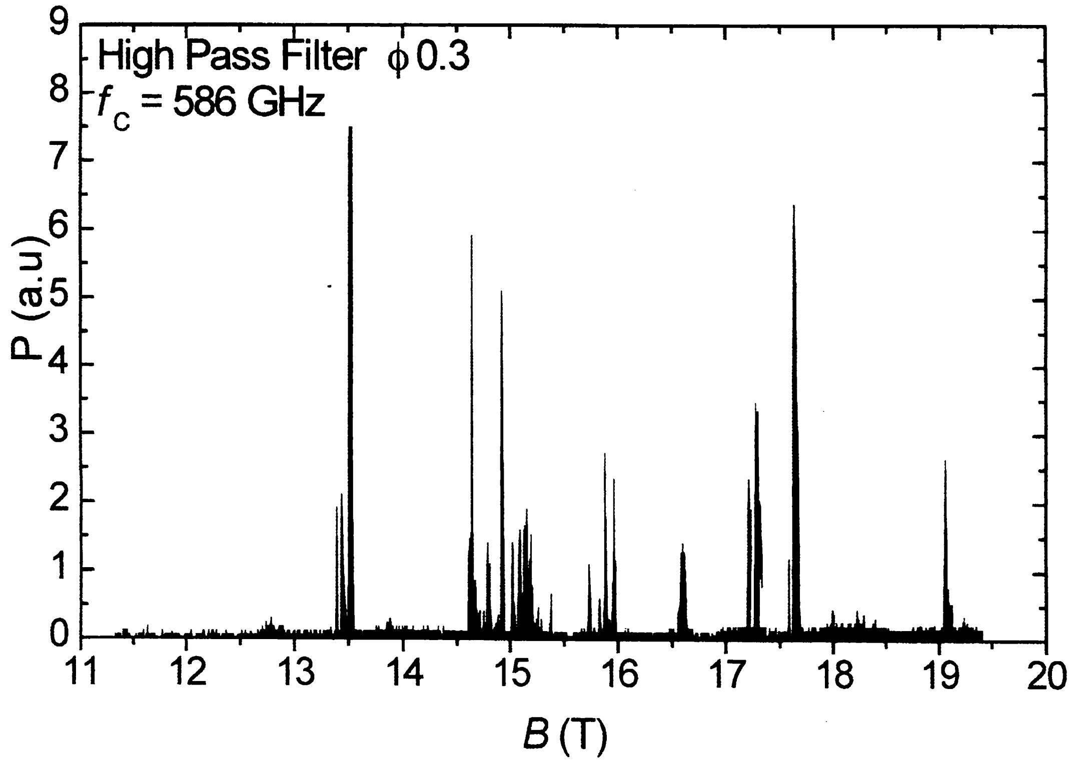

Fig. 7 Radiation power measured after a high pass filter with a circular waveguide whose Dimeter is 0.3 mm are summarized as a function of magnetic field intensity.

All frequencies estimated from the field intensities where the power peak appears are plotted in Fig. 8. The cavity modes identified from the estimated frequencies are indicated in the figure. There are many cavity modes excited at both fundamental and second harmonic operations. As described already, the pulse duration of all operation modes can be extended to around 1ms, if the timing of the electron beam injection is adjusted at the top of magnetic field pulse. Therefore, these radiations observed in the frequency range from 0.4 THz to 1 THz are useful for their applications to high power THz Technologies.

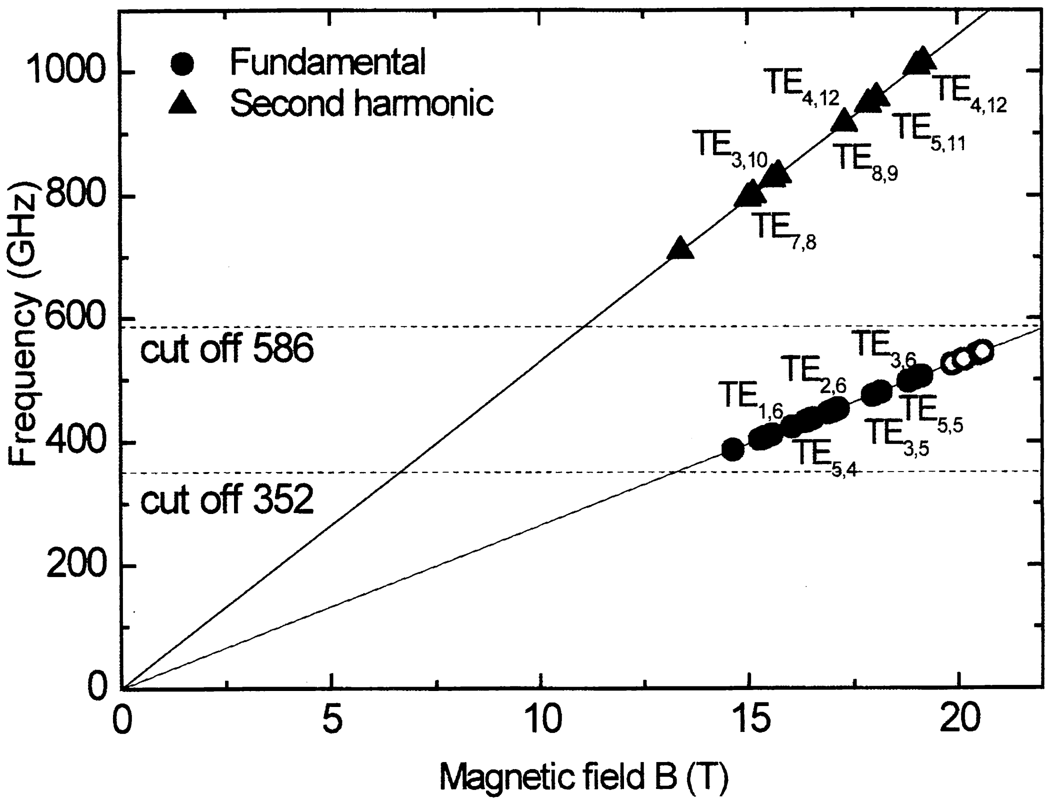

Fig. 8. All frequencies estimated from the field intensity where the radiation peaks appear are plotted as functions of magnetic field intensity. Several cavity modes identified from the expected frequency, are indicated in the figure.

3-3 Consideration on the experimental study

$TE_{4,12}$ cavity mode has achieved the breakthrough of 1 THz at the second harmonic operation[10]. Now, we are considering the excitation condition of the mode on the basis of calculation results for coupling constant C_{BF} as function of injection point of beam electrons. C_{BF} is given as follows,

$$C_{BF} = \frac{\div^2_{mn} J^2_{m\pm s}(\div_{mn} {}^{R_e}\!/_{R})}{\partial R^2 (\div^2_{mn} - m^2) J^2_m(\div_{mn})} \qquad 1)$$

m = 4

n = 12

s = 2

where m and n are azimuthal and radial mode number of the cavity mode, s the harmonic number, $J(x)$ Bessel function of the second kind, r_c the radius of the cavity and xx xx th zero of J' . In the case of $TE_{4,12}$ mode at the second harmonic operation, m=4, n=12 and s=2. Fig. 9 shows the calculation results of C_{BF} as a function of an injection radius r of electron beam normalized by a cavity radius r_c. The vertical line indicated at around r/r_c =0.2 shows the real injection radius of electron beam r_b estimated by following simple formula.

$$r_b / r_c = r_G / r_c (B_G / B_c)^{1/2} \qquad 2)$$

where r_G is a radius of emitting area of gun cathode, B_G and B_c are magnetic field intensities at the emitting area of gun cathode and cavity region, respectively.

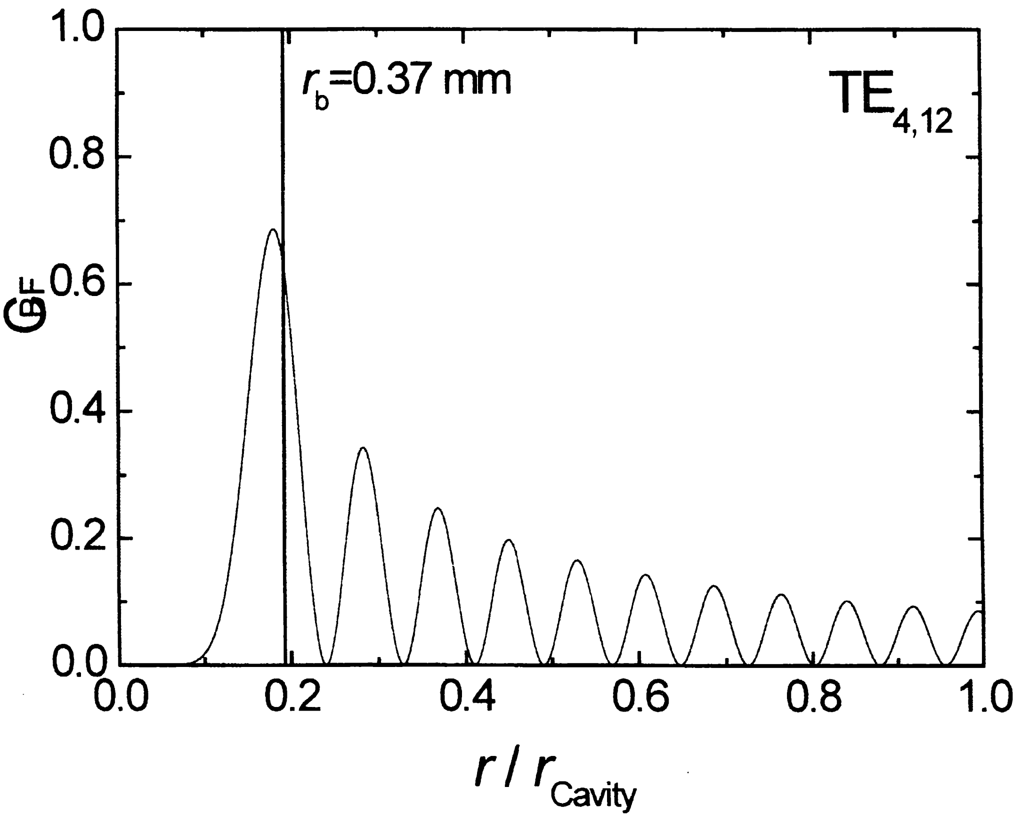

Fig. 9 Coupling coefficient C_{BF} as function of injection radius r of electron beam normalized by the cavity radius rc, The vertical line shows the real injection radius rb estimated by equation 2)

As seen in this figure, the electron beam is injected near the first maximum point of the coupling coefficient. This means that the single mode operation of $TE_{4,12}$ mode even at the second harmonic is reasonable.

5. Summary

In the previous paper[10), we have already describe the breakthrough of 1 THz which our gyrotron with 20.5 T pulse magnet has achieved. After then, we tried some detailed experiments including long pulse operation at THz frequency range by adjusting the timing of electron beam injection at the top of magnetic field pulse. We have succeeded in extending the operation pulse width up to 1 ms even at the second harmonic in the frequency range of THz. It is very important for the application of our THz gyrotron to many high power THz technologies. On the basis of this success, we have designed the next gyrotron, Gyrotron FU CW III with a 20 T superconducting magnet, which operates in THz frequency range at the second harmonics. The 20 T magnet has already arrived at FIR FU and construction of a demountable gyrotron tube will be completed soon. We hope to operate it several months later in complete CW mode.

Other additional results of the operation results of the THz gyrotron are also described. In the range of magnetic field intensity between 4T and 20 T, there are many cavity modes excited at both fundamental and the second harmonics. The pulse duration of all of these modes can be extended up to around 1 ms, as demonstrated for second harmonic operations of $TE_{4,12}$ and $TE_{10,8}$ modes. Therefore, all of these modes will be useful for application of the gyrotron to many high power THz technologies.

From the view point of gyrotron application, CW operation in long time is desired. In FIR FU, development of new gyrotron series, named Gyrotron FU CW Series are being advanced. The first gyrotron, Gyrotron FU CW I, has already been developed. The out put frequency and power are 300 GHz and 1.75 kW in CW, respectively. The second gyrotron, Gyrotron FU CW II has also been constructed and tested. Designed mode is $TE_{2,6}$ at the second harmonic, the frequency 394.6 GHz and the output power 100 W. This radiation power will be used for enhancement of NMR sensitivity by use of DNP method. The third gyrotron, Gyrotron FU CW III with 20 T superconducting magnet is being constructed. It is designed on the basis of successful experiment of the THz gyrotron with a pulse magnet described in this paper. We hope to operate soon the gyrotron in CW mode.

Acknowledgement

This work is supported partially by the special fund for education and research from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) in Japan.

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