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Abstract

A gyrotron with an axis-encircling electron beam is useful for high frequency operation, because the high beam efficiency is kept even at high harmonic of electron–cyclotron resonance. We have designed and constructed such a gyrotron with a permanent magnet. The gyrotron has already succeeded in operation at the third harmonic and the fourth harmonic resonances. The operation frequencies are 89.3 and 112.7 GHz, respectively. Operation cavity modes are TE_{311} and TE_{411}. The permanent magnet system consists of many magnet elements made of NbFeB and additional coils for controlling the field intensities in cavity and electron gun regions. The magnetic field at the cavity region can be varied from 0.97 to 1.18 T. At the optimum condition of the magnetic field intensity, the output power at the third harmonic operation is 2.5 kW. The operation is pulsed, the pulse length is 1 ms and the repetition frequency is 1 Hz. The beam energy and current are 40 kV and 1.2 or 1.3 A. Starting current, beam efficiency and emission pattern also have been measured. In this paper, the operation results of the gyrotron and comparison with the computer simulation results are described.

Keywords: High harmonic gyrotron; Permanent magnet; Axis-encircling electron beam

1. Introduction

Development of gyrotrons is being advanced in two ways. One is a development of high-power millimetre wave gyrotrons. At the present, a gyrotron with a diamond window has achieved 2 MW output power with the frequency of 170 GHz under a long pulse operation. The pulse length is several seconds. Such high-power gyrotrons are being used for electron–cyclotron heating of nuclear fusion plasmas. The other is a development of high-frequency medium-power gyrotrons as millimetre to submillimetre wave radiation sources for application to new far-infrared technologies. The frequency attains 890 GHz, keeping the output power several 10 W to several 10 kW.

Our gyrotrons developed in Fukui University, Research Center for Development of Far Infrared Region (FIR FU) belong to the second type. In FIR FU, we have already developed the Gyrotron FU Series which consists of 9 gyrotrons. The gyrotron series has achieved frequency tunability in wide range (from 38 to 889 GHz). The highest frequency corresponds to a wavelength of 337 μm. This is the current record for high-frequency operation of a gyrotron.

In order to develop such high-frequency gyrotrons, we should use a high magnetic field which is generated by a superconducting magnet [1] and/or operation at a high harmonic of electron–cyclotron frequency [2]. In our recent gyrotron, Gyrotron FU IVA, a 17 T superconducting magnet is used. In this case, the operation of the device is complicated, because we need to use cryogenic facilities, for example, transferring liquid helium from a container to the cryostat and recovering evaporated helium to liquifying system.

Recently, we have developed a high-harmonic gyrotron with an axis-encircling electron beam and a permanent magnet instead of a superconducting magnet. The treatment is much simplified [3], but the field intensity is quite low (around 1 T) in comparison with a superconducting magnet. We have to use higher harmonic operations in order to increase the frequency of the gyrotron. A gyrotron with an axis-encircling electron beam (so-called large orbit gyrotron, LOG see Fig. 1) is suitable for nth harmonic operation, when the TE_{n11} cavity mode is employed. In this case, an axis-encircling electron beam feels n cycles of alternating electric field during one cycle of the electron gyration. Therefore, when the frequency of the electromagnetic wave f is equal to n times of the electron–cyclotron frequency f_c ($f = nf_c$), the interaction between an electron and electromagnetic wave is optimized and highly efficient operation is expected. In addition, the mode selection is excellent, because only the TE_{n11} cavity mode is excited in the condition of $f = nf_c$ without mode competition [4].

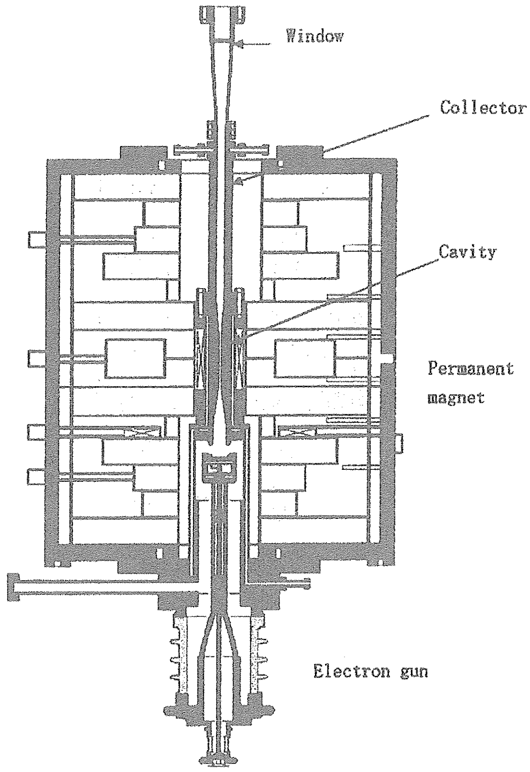

Fig. 1. Schematic drawing of LOG device.

In the case of a conventional gyrotron, higher harmonic operation is difficult to obtain. The Gyrotron FU Series attained mainly second harmonic operations. The third harmonic operation is very rare. The efficiency decreases as the harmonic number increases. On the other hand, in the case of LOG, the higher harmonic operation ($n = 3$, 4, 5) is easily excited. This is the most important advantage of LOG [5,6].

We have already constructed a LOG with a permanent magnet and finished preliminary tests successfully. In this paper, the design, constructed device and results of operation test are described.

2. Operation mechanism and advantages of LOG

LOG is characterized by the trajectory of the electron beam in the cavity. The beam electron gyrates around the centre axis of the cavity, it is a so-called 'axis-encircling electron beam' [7], while in a conventional gyrotron, the beam electron rotates around a gyration centre located on a concentric circle of a cylindrical cavity. When we use an axis-encircling electron beam and TE_{nm1} cavity mode, the interaction between an electron beam and high-frequency electromagnetic wave is optimized at the *n*th harmonic operation. Otherwise, the interaction does not occur. Therefore, we can expect highly efficient operation at *n*th harmonics ($f=nf_c$) and good mode selection of the TE_{nm1}. This means that mode competition with lower harmonic modes is removed. This is an important advantage, because mode competition is the most severe problem in high-harmonic gyrotrons. From such a viewpoint, LOG is most suitable for high harmonic operation.

In the LOGs developed in the past, an axis-encircling electron beam was generated by the non-adiabatic effect of a cusp field or electron–cyclotron resonance acceleration of an electron in the vertical direction. In both cases, resulting electrons have large value of ripple, that is, the displacement of the guiding centre from the centre axis of the resonant cavity is large. This effect reduces the operation efficiency and makes the starting beam current for high harmonic operation higher.

Instead of such methods, we are using a carefully designed electron gun with an optimized profile of magnetic field to generate an axis-encircling electron beam with small ripples. As a result, we can succeed in obtaining third and fourth harmonics using rather small electron beam power.

3. Experimental apparatus and procedures

In Fig. 1, a schematic drawing of LOG with a permanent magnet system is shown.

3.1. Magnet system

The permanent magnet consists of many elements of NdFeB as shown in Fig. 2. The structure is carefully designed to generate an appropriate profile of magnetic field on the centre axis of the magnet system. Each layer made of NdFeB is divided into 12 elements in the azimuthal direction. An arrow indicates the direction of magnetization of each layer. The resulting field profile on the centre axis is shown in Fig. 3. The horizontal axis shows the distance *z* from the centre of the magnet system. The measured maximum field intensity is 1.0729 T and the uniformity in the region indicated by 'A' is higher than 2%. The permanent magnet system has an additional coil in the electron gun region to control the profile of the

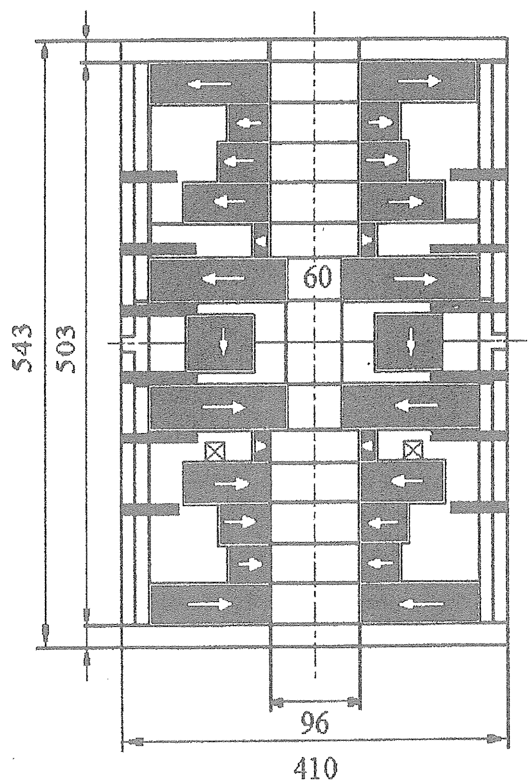

Fig. 2. Structure of the permanent magnet system. Magnetization of each element is shown by an arrow. The sizes are in millimetre.

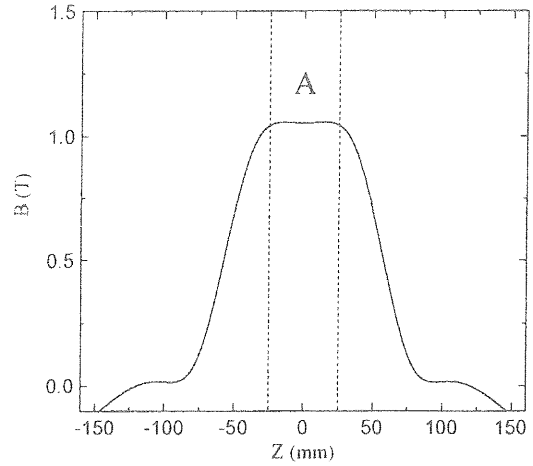

Fig. 3. Distribution of magnetic field intensity B (T) of a LOG magnet system.

magnetic field near the cathode of the electron gun. It is important for the generation of a high-quality electron beam with small ripple. The coil consists of ten layers. Each layer has ten turns of winding. The coil current can be swept from -13 to $+13$ A and additional field intensity supplied by the coil near cathode region is 7×10^{-4} T/A.

3.2. Gyrotron tube

In Fig. 4, the structure of a tube of LOG is shown. The electron gun is designed carefully to generate a high-quality axis-encircling electron beam. Electrons are emitted from the circular emitting area made of LaB_6 on a cathode surface and accelerated by the potential difference between the cathode and the body including a cavity. Electrons feel a gradually increasing magnetic field and obtain vertical energy. Finally, a hollow axis-encircling electron beam is formed and injected into the cavity. This is the most important point for our LOG, which is different from conventional gyrotrons [8].

In the case of nth harmonic operation, the cavity should be designed so that the resonant frequency of the TE_{n11} cavity mode is equal to n times of electron-cyclotron frequency. Fig. 5 shows detailed dimensions of the cavity, which is optimized

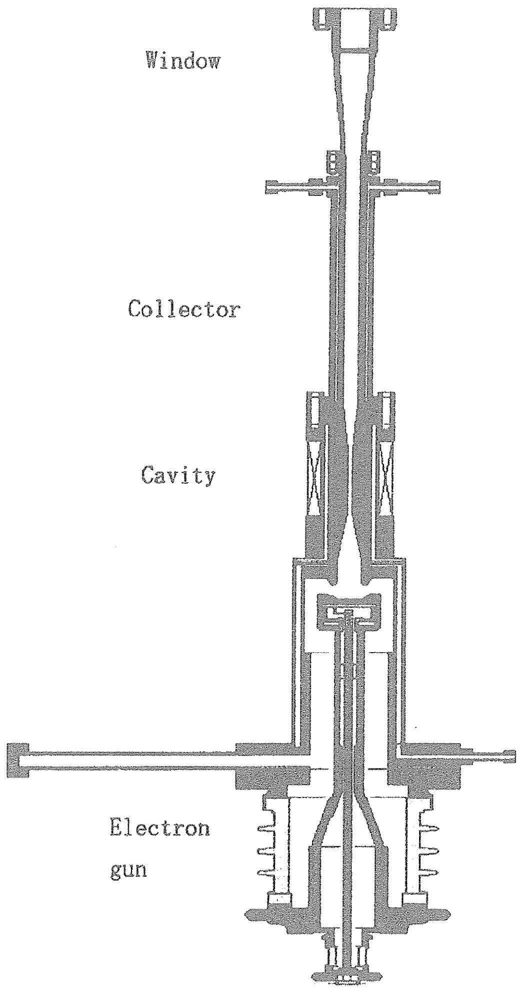

Fig. 4. Schematic drawing of the gyrotron tube.

for fourth harmonic operation. In this cavity, the TE_{411} cavity mode is excited near a field intensity of 1 T. The whole tube is demountable, which allows every component including a cavity, a window and an electron gun to be changed.

An additional coil is installed at the cavity region to control the field intensity precisely. The coil consists of seven layers and 74 total windings. The coil is operated in pulse mode. The pulse width is 18 ms and repetition rate is 1 Hz. The coil current can be changed from -20 to $+20$ A and

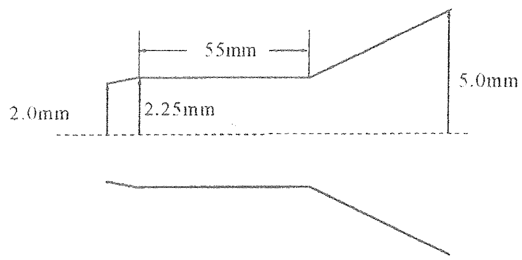

Fig. 5. Configuration of the resonant cavity.

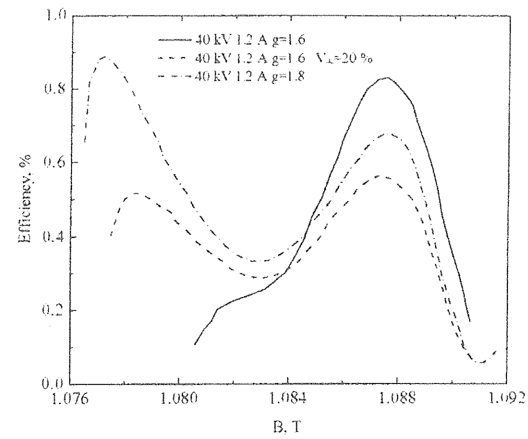

Fig. 6. Computer simulation result for operation efficiency E as a function of magnetic field intensity B (T).

additional field intensity at the cavity region is 69.8×10^{-4} T/A.

The inside of the tube is pumped out by an ion pump and a turbo molecular pump. The pressure is kept at around 10^{-5} Pa. An electromagnetic wave generated in a cavity is transmitted through a circular waveguide system and emitted from a vacuum window made of BN.

3.3. Experimental procedure and conditions

The gyrotron is operated in pulse mode. The typical pulse width is 1 ms and the duty ratio is 0.1%. An acceleration voltage and a beam current can be increased up to 40 kV and 1.5 A, respectively. A pyro-electric detector is used for measurement of the emitted electromagnetic wave. When we observe an emission pattern, an array of pyro-electric detectors is swept at around 1000 mm above the vacuum window. Data obtained by each pyro-electric detector is stored in a computer and it is analyzed to demonstrate the emission pattern, after the measurement is finished.

The absolute value of output power is measured by water load, which is compared with heating due to a 1 W electric heater. A frequency metre using a cylindrical cavity or a Fabry–Perot interferometer is used for frequency measurement.

4. Experimental results

We have already finished operation test of two cavities. Cavity 1 is optimized for fourth harmonic operation using TE_{411} mode, while Cavity 2 for third harmonic using TE_{311} mode. The test results are as follows.

4.1. Cavity 1 for fourth harmonic operation

As described in the previous section, TE_{411} cavity mode is used for fourth harmonic operation. Cavity 1 is designed so that the radius is optimized for the fourth harmonic operation. The dimensions of the cavity are shown in Fig. 5.

In Fig. 6, computer simulation results for operation efficiency as function of magnetic field intensity at the cavity region are presented. The parameter is a pitch factor of beam electrons g. From the simulation result, it is expected that the fourth harmonic operation occurs near the field intensity of 1.08 T. The efficiency should be less than 1%.

In Fig. 7, a typical operation result observed on an oscilloscope is demonstrated. It is seen that a stable operation occurs in pulse mode. The pulse length is about 1ms and repetition rate is 1 Hz. The acceleration voltage is 40 kV and the beam current is around 1.2 A. The absolute value of output power measured by a water load was 0.47 kW. Corresponding operation efficiency is about 0.98%. The frequency measured by a frequency metre was 112.696 GHz.

The output power is plotted in Fig. 8 as a function of acceleration voltage V and in Fig. 9 as a function of the magnetic field intensity B. The parameter is a current I_{gc} of one of the additional

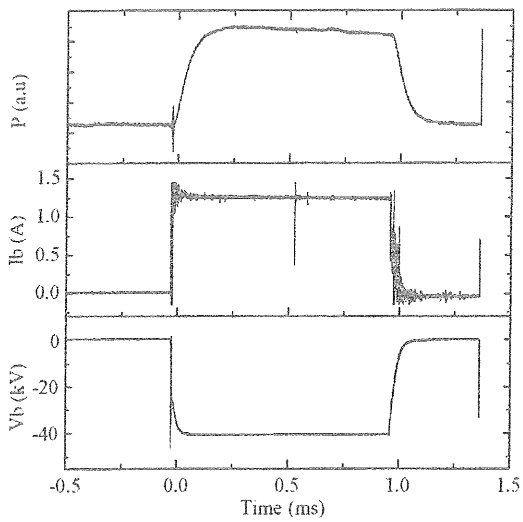

Fig. 7. Observed patterns on an oscilloscope for fourth harmonic operation using the TE_{411} cavity mode. Output power (P), acceleration voltage (V) and beam current (I) are shown.

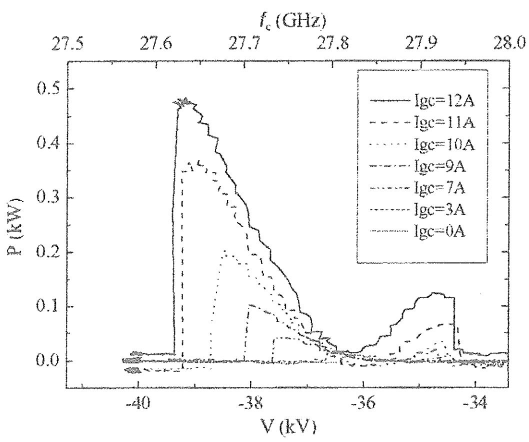

Fig. 8. Output power P as functions of cyclotron frequency f_c (Acceleration voltage V is varied.).

coils installed at the electron gun region. When I_{gc} is changed, the pitch factor of beam electron g changes. Such an effect results in the change of operation efficiency. In both cases, the corresponding electron–cyclotron frequency f_c is indicated on the above horizontal axis. Both results are similar to the computer simulation results shown in Fig. 6.

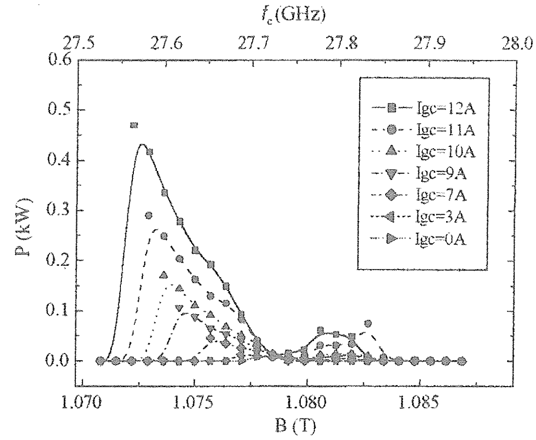

Fig. 9. Output power P as a function of the cyclotron frequency f_c (Field intensity B is varied.).

Fig. 10 shows emission pattern measured at 1030 mm above the output (vacuum) window. A kind of standing wave structure in the azimuthal direction is seen. This means a counter-rotating TE^{-}_{411} mode co-exists with a rotating mode TE^{+}_{411}. From the observed emission pattern, the standing wave ratio ρ can be decided and then the ratio of counter-rotating TE_{411} mode is estimated. P was around 1.3 and ratios of both counter-rotating and rotating modes were 5% and 95%. Usually, a counter-rotating mode is not excited. Now, we are studying on the reason why such mode exists.

The third harmonic operation using TE_{311} mode has also been achieved by Cavity 1 at a slightly higher field intensity. Fig. 11 shows the output power P as a function of magnetic field intensity B. There are several peaks of output power. Three peaks appearing from 1.15 to 1.2 T are third harmonic operation due to excitation of TE_{311}, TE_{312} and TE_{313} cavity modes. Measured frequency for TE_{311} mode is 89.3 GHz. Frequencies for TE_{312} and TE_{313} are a little bit higher. Two peaks appearing below 1.1 T correspond to fourth harmonic operation due to excitation of TE_{411} and TE_{412} modes.

The absolute value of output powers measured by a water load were 1.7 kW for the third harmonic and the efficiency was 3.3%.

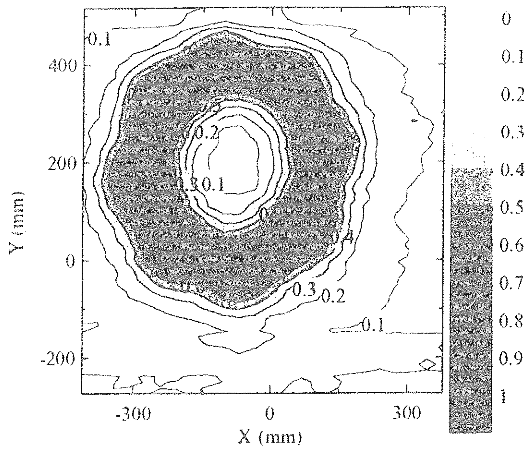

Fig. 10. Emission pattern observed at 1030 mm above the output window for the case of fourth harmonic operation using the TE_{411} cavity mode.

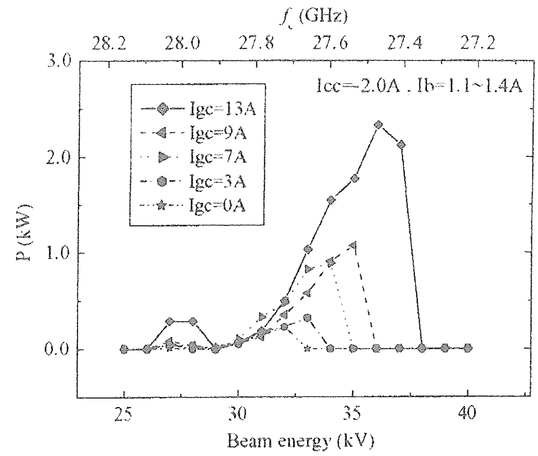

Fig. 12. Output power (P) as a function of cathode voltage for operation at third harmonic of the cyclotron frequency using the TE_{311} cavity mode.

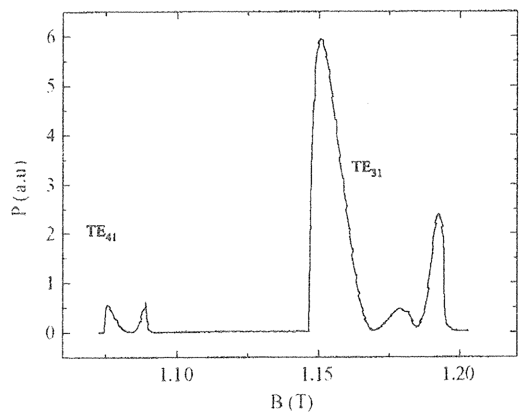

Fig 11. Output power (P) as a function of magnetic field intensity (B).

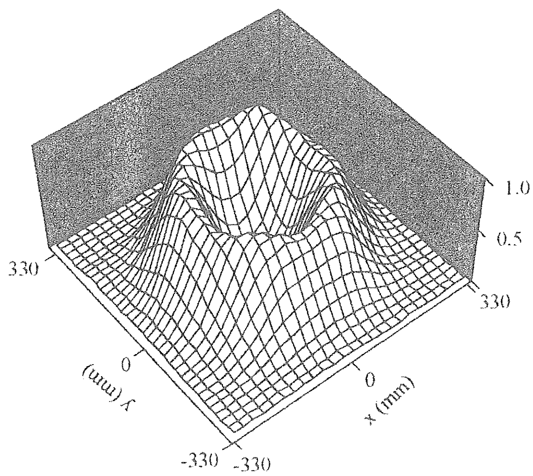

Fig. 13. Emission pattern observed at 1030 mm above the output window for the case of third harmonic operation using the TE_{311} cavity mode.

4.2. *Cavity 2 for third harmonic operation*

Cavity 2 is optimized for third harmonic operation using the TE_{311} cavity mode. The radius and length are 2.36 and 50 mm, respectively.

In Fig. 12, an output power P of third harmonic as functions of acceleration voltage V_b with current of additional coil I_{gc} as a parameter is shown. When V_b is changed, the electron–cyclotron frequency f_c changes as well. The range of f_c where the fourth harmonic operation occurs is increased and increases with I_{gc}. The maximum power and corresponding efficiency reach 2.5 kW and 6.25%, respectively. Increase of a pitch factor with increased I_{gc} affects operation efficiency and finally output power. The measured frequency is 84.88 GHz.

Fig. 13 demonstrates an emission pattern for third harmonic operation due to excitation of TE_{311} cavity mode. A feature of pure TE_{311} mode appears in the emission pattern. It is a manifestation of good mode selection in LOG. This is one of important advantages of LOG for development of high harmonic gyrotron.

5. Conclusion

We have constructed a large orbit gyrotron (LOG) with a permanent magnet system. The electron gun and the profile of magnetic field distribution are optimized for generation of a high-quality axis-encircling electron beam with a small ripple and large pitch factor.

Operation test for two cavities were carried out successfully. In the case of Cavity 1, which is optimized for fourth harmonic operation using TE_{411} cavity mode, we have obtained an output power of 0.47 kW, a corresponding efficiency of 0.96% and the frequency of 112.7 GHz. We have achieved third harmonic operation using Cavity 1. In this case, the output power is 1.7 kW, corresponding efficiency 3.3% and the frequency 89.3 GHz. On the other hand, Cavity 2 is optimized for the third harmonic operation by using the TE_{311} cavity mode. Test results are as follows. Output power is 2.5 kW, the efficiency 6.25% and the frequency 84.88 GHz. In both cases, operation is in a pulse regime. The pulse width is 1ms and repetition rate is 1 Hz. Acceleration voltage and beam current are typically 40 kW and 1.2 or 1.3 A, respectively.

Recently, using Cavity 1 we succeeded in operating the gyrotron at fifth harmonic exciting the TE_{511} cavity mode. The output power is rather low, of the order of 10 W. The frequency measured by a Fabry–Perot interferometer is 138 GHz.

Operations at the third, the fourth and even the fifth harmonics are achieved under an acceleration voltage of only 40 kV. At present, the frequency range is in the millimetre wave length region. In future, we are intending to construct LOG with a super-conducting magnet system for increasing the frequency beyond 1 THz.

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