Broadband Continuously Frequency Tunable Gyrotron for 600 MHz DNP-NMR Spectroscopy

Ryosuke IKEDA, Yuusuke YAMAGUCHI[1)], Yoshinori TATEMATSU[1)], Toshitaka IDEHARA[1)], Isamu OGAWA[1)], Teruo SAITO[1)], Yoh MATSUKI[2)] and Toshimichi FUJIWARA[2)]

Japan Atomic Energy Agency (JAEA), Mukoyama, 801-1 Naka-shi, Ibaraki 311-0193, Japan

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

[2)]*Institute for Protein Research, Osaka University, Yamadaoka, 3-2 Suita-shi, Osaka 565-0871, Japan*

(Received 17 February 2014 / Accepted 24 March 2014)

A broadband continuously frequency tunable gyrotron with a triode-type magnetron injection gun was developed as power source for analysis of protein structures. The $TE_{7,3}$ oscillation mode was selected to avoid mode competitions in the high magnetic field side. Axial modes of the $TE_{7,3,-10}$ were sequentially excited by changing the cavity magnetic field, and frequency tuning of about 4 GHz around 395 GHz was observed with output power greater than 50 W. The frequency also varied about 1 GHz as the anode–cathode voltage varied. Thus, the broadest tuning bandwidth in the 400 GHz band gyrotrons was achieved.

Keywords: gyrotron, Gyro-BWO, frequency tuning, sub-millimeter wave, dynamic nuclear polarization

DOI: 10.1585/pfr.9.1206058

Low-power and high-frequency gyrotrons are used in dynamic nuclear polarization in which sub-millimeter waves enhance the sensitivity of solid-state nuclear magnetic resonance spectroscopy for the structural analysis of complex proteins (DNP-NMR) [1, 2]. To effectively raise the sensitivity, it is necessary to irradiate the protein sample with sub-millimeter waves of several watts at optimal frequencies, for example, 394.0 GHz or 395.2 GHz for 600 MHz DNP-NMR. However, frequency lag in the order of 100 MHz is created from fabrication errors of a few micrometers in the cavity diameter. Therefore, fine continuously frequency tunability is required to optimize the frequency. Frequency tuning is performed by exciting axial modes at higher magnetic field strength than that of the usual gyrotron oscillation. This is the gyrotron backward wave oscillator (Gyro-BWO) condition resulting from the interaction of the backward wave in the cavity resonator and the electron beam [3]. Figure 1 (a) shows the dispersion relation of the interaction conditions. The axial wave number $k_{//}$ is almost equal to $q\pi/L_c$, where q and L_c are the axial mode number and cavity length, respectively. The oscillation frequency in the Gyro-BWO region, where q becomes negative, varies by changing the electron cyclotron frequency as a function of the cavity magnetic field and axial electron velocity injected into the cavity. Axial modes have multi peak electric-field profiles in the cavity, as shown in Fig. 1 (b). Conventional gyrotrons oscillate at $q = 1$. To date, remarkable experimental results of continuously frequency tunability by using the Gyro-BWO oscillation have been reported in the sub-THz region between 100 GHz and 500 GHz [4–12].

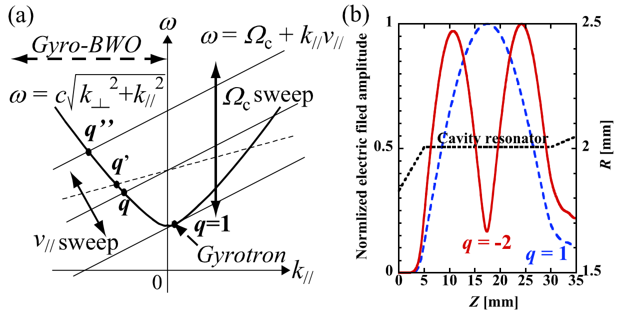

Fig. 1 (a) Dispersion relation of Gyro-BWO oscillation. (b) Schematic view of the axial mode in the cavity resonator.

At FIR FU, we have demonstrated frequency tuning from 394.6 GHz to 396.2 GHz, including the optimum frequency of 395.2 GHz, and the output power of less than 30 W at fundamental resonance around 14.5 T [6]. The tuning bandwidth of 1.6 GHz was the broadest in 400 GHz band gyrotrons [13]. This gyrotron was used for 600 MHz DNP-NMR experiment [14]. In addition, gyrotron frequency changes around 394 GHz were also attempted and the tuning bandwidth of 1.5 GHz was obtained [15]. Although the designed oscillation mode for these gyrotrons was the $TE_{0,6}$ mode, the tuning bandwidth was limited by a competition mode, such as the $TE_{7,4}$ mode, in the high magnetic field side. To cover the above-mentioned optimal frequencies with one gyrotron, a tuning bandwidth of

author's e-mail: ikeda.ryosuke@jaea.go.jp

more than 2 GHz is required. Moreover, it is necessary to sufficiently separate the design mode from possible competing modes in the high magnetic field side. The $TE_{7,3}$ mode was selected to satisfy these conditions.

The manufactured gyrotron is of the demountable type, and is equipped with a Helium-free 15 T superconducting magnet (room temperature bore diameter: 52 mm) and a gun coil to adjust the electron beam radius. The cavity radius and length are 2.005 mm and 25.0 mm, respectively. The long cavity was introduced to reduce oscillation starting currents of the axial mode by enhancing a quality factor of the cavity. A triode-type magnetron injection gun was used to control the pitch factor ($\upsilon_\perp/\upsilon_{//}$) by changing the anode–cathode voltage. Parameters $\upsilon_\perp$ and $\upsilon_{//}$ are velocities perpendicular and parallel to the magnetic field line, respectively. The output window is a single-crystal sapphire, whose thickness is optimized for 394 GHz.

Figure 2 shows the magnetic field dependence of the oscillation frequency, output power, and oscillation starting current. The operation conditions are cathode voltage V_k = 15 kV, anode–cathode voltage V_{ak} = 6 kV, beam current $I_b \sim$ 400 mA, pulse repetition frequency of 1 Hz, and duty ratio of 2%. The oscillation frequency was measured using a heterodyne receiver. The output power was estimated from the water-temperature differences between the input and output of a dummy load. The oscillation starting current was measured using a pyroelectric detector with increasing beam current. The $TE_{2,5,q}$ mode oscillated up to $B_c \sim$ 14.27 T. The oscillation of the $TE_{7,3,q}$ mode started

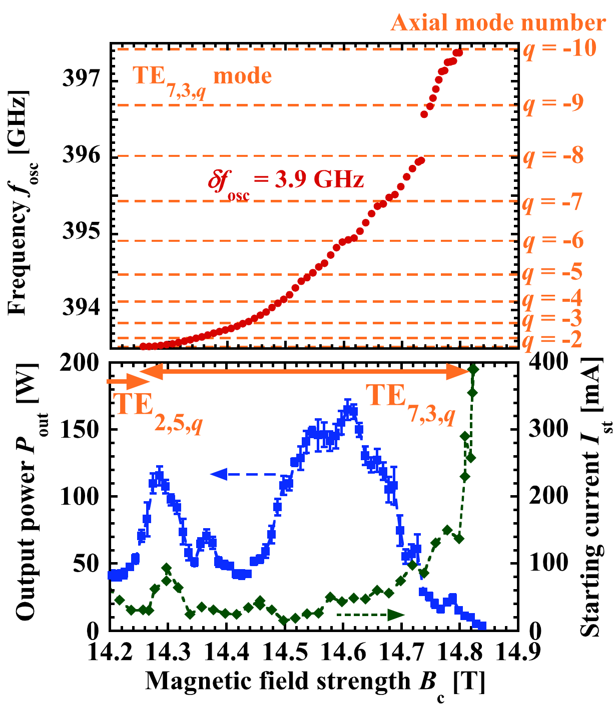

Fig. 2 Magnetic field dependence of the oscillation frequency, output power, and starting current.

from $B_c \sim$ 14.25 T, and the oscillation frequency varied smoothly from 393.5 GHz to 397.4 GHz. The calculated frequencies of the axial mode numbers are represented by a broken line in Fig. 2. It is estimated that the axial mode number was excited up to $q = -10$. The output power increased up to 120 W in the conventional gyrotron oscillation region (q = 1). The output power gradually decreased as it deviated from the magnetic field of the gyrotron oscillation. With increasing magnetic field, the output power increased again up to 170 W, which exceeded the output power of the gyrotron oscillation. The output power decreased again for $B_c >$ 14.6 T with increasing starting current. Although frequency jump was observed at $B_c \sim$ 14.74 T, its occurrence is not fully understood. The frequency tuning bandwidth was in the 3.9 GHz range, which includes the optimal frequencies 394.0 GHz and 395.2 GHz for 600 MHz DNP-NMR spectroscopy; furthermore a sufficient output power of more than 50 W was achieved. This result broke previous records of tuning bandwidth attained in 400 GHz band gyrotrons.

The frequency can also be tuned by changing the axial velocity of the electron beam. Figure 3 shows the anode–cathode voltage dependence of the oscillation frequency, output power, and oscillation starting current for the fixed magnetic field of B_c = 14.6 T. A frequency tuning bandwidth of 0.94 GHz was observed. This frequency tuning may be realized by varying the axial mode between $q = -5$ and -7. Output power of more than 50 W was obtained with $V_{ak} >$ 4.5 kV. The oscillation stopped when the anode–cathode voltage dropped below 3.5 kV because the pitch factor decreased and the starting current increased. Degradation of the output power was observed in the case of $V_{ak} >$ 6.5 kV. This might be caused by the reflection of the electron beam before the cavity owing to an extremely high pitch factor. The frequency tuning bandwidth obtained by changing the anode–cathode voltage is narrower than that obtained by sweeping the magnetic field. However, in the case of changing the anode–cathode voltage,

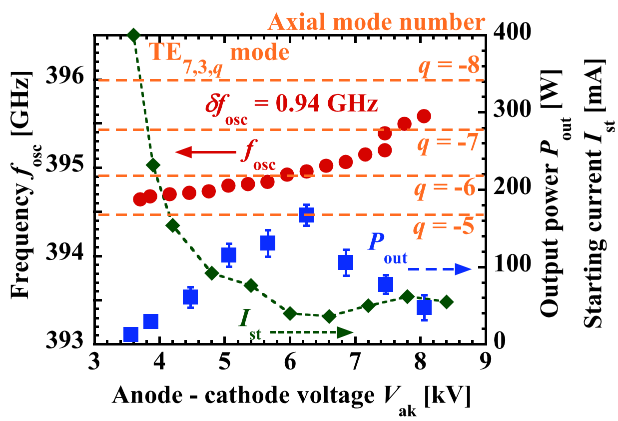

Fig. 3 Anode–cathode voltage dependence of the oscillation frequency, output power, and starting current.

a much faster sweep and finer adjustments of the oscillation frequency are possible than the case of the magnetic field sweep. Therefore, it is expected that optimal oscillation frequencies can be obtained by combining the two methods.

This work was partially supported by a Grant-in-Aid for Young Scientists (B) 23760307. The authors would like to thank Mr. T. Kuwahara and Mr. T. Kanemaki of FIR FU for technical support and gyrotron fabrication.

[1] V.S. Bajaj *et al*., J. Magn. Reson. **160**, 85 (2003).
[2] Y. Matsuki *et al*., Phys. Chem. Chem. Phys. **12**, 5799 (2010).
[3] G.S. Nusinovich *et al*., IEEE Trans. Plasma Sci. **24**, 620 (1996).
[4] M.K. Hornstein *et al*., IEEE Trans. Electron Device **52**, 798 (2005).
[5] T.H. Chang *et al*., J. Appl. Phys. **105**, 063304-1 (2009).
[6] T. Idehara *et al*., J Infrared Milli Terahz Waves **31**, 775 (2010).
[7] A.C. Torrezan *et al*., IEEE Trans. Plasma Sci. **38**, 1150 (2010).
[8] A.C. Torrezan *et al*., IEEE Trans. Electron Devices **58**, 2777 (2011).
[9] A.B. Barnes *et al*., J. Magn. Reson. **221**, 147 (2012).
[10] D.S. Tax *et al*., IEEE Trans. Plasma Sci. **41**, 862 (2013).
[11] W. He *et al*., PRL **110**, 165101 (2013).
[12] Y. Yamaguchi *et al*., 38th IRMMW-THz, Mo-P1-53 (2013).
[13] E.A. Nanni *et al*., IEEE Trans. Terahz Sci. Technol. **1**, 145 (2011).
[14] Y. Matsuki *et al*., J. Magn. Reson. **225**, 1 (2012).
[15] R. Ikeda *et al*., 37th IRMMW-THz, Tue-Pos-29 (2012).