Development of Gyrotron FU CW IIA for 600 MHz and 300 MHz DNP-NMR experiments at the University of Warwick

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Abstract—**On the basis of successful development of Gyrotron FU CW II, a similar gyrotron FU CW IIA is being developed for both 600 MHz and 300 MHz DNP-NMR experiments at the University of Warwick in UK. The frequencies of the gyrotron are 394.6 GHz at the second harmonic and 200 GHz at fundamental that correspond to frequencies 600 MHz and 200 GHz of DNP-NMR spectroscopy. The output powers are around 30 W and 200 W, respectively. Both operations are in CW modes.**

I. Introduction And Background

RECENTLY, demands on using of the gyrotrons as a millimeter to submillimeter wave sources for sensitivity enhancement of NMR spectroscopy are intensively increasing due to successful experiments in DNP-NMR spectroscopy (for example in [1]) and many attractive applications in new physical and biological researches which are characterized by poor NMR sensitivity. In this respect we have developed a Gyrotron FU CW II with frequency of 394.6 GHz and supplied for protein research at Osaka University [2].

On the basis of successful development of Gyrotron FU CW II, a similar gyrotron FU CW IIA is being developed for both 600 MHz and 300 MHz DNP-NMR experiments at the University of Warwick in UK. It utilizes a 9.2 superconducting magnet. The gyrotron operates at both fundamental and second cyclotron harmonics.

II. Gyrotron Design

The gyrotron tubes are installed inside an 89 mm cryostat bore diameter of 9.2 superconducting magnet. The cavity is optimized for operating the TE_{16} mode at second harmonic with the frequency of nearly 394.6 GHz which is corresponding to 600 MHz proton DNP-NMR frequency, and $TE_{4,2}$ or $TE_{1,3}$ modes at the fundamental cyclotron harmonic for nearly 300 MHz DNP-NMR. The cavity radius and length are 2.175 mm and 19 mm, respectively. The main operating mode, $TE_{1,6}$ is well-isolated from other competitors by injecting electron beam with radius of 0.47 mm.

The high quality helical electron beam is produced by a triode-type magnetron injection gun with cathode diameter of 9 mm. The gun coil with maximum magnetic field of 0.15 T at the current of 300 A, is installed around the cathode to adjust beam radius at the entrance of cavity. The cryostat of superconducting magnet has a height of 1.2 m. The total tube height including electron gun and window is about 2.32 m. The gyroton tube fabrication and installation have been completed. It is under the operation test in FIR Center University of Fukui. Fig. 1 shows the cross-sectional view of gyrotron. Cavity is installed at the center of superconducting magnet.

The cavity and collector are cooled by water flowing to keep the tube temperature at a permissible level during the long period of operations. The output window is made of a sapphire disk. Two pumping system are located after the electron gun and before the output window to evacuate outgassing produced inside tube and to maintain vacuum condition during the operations.

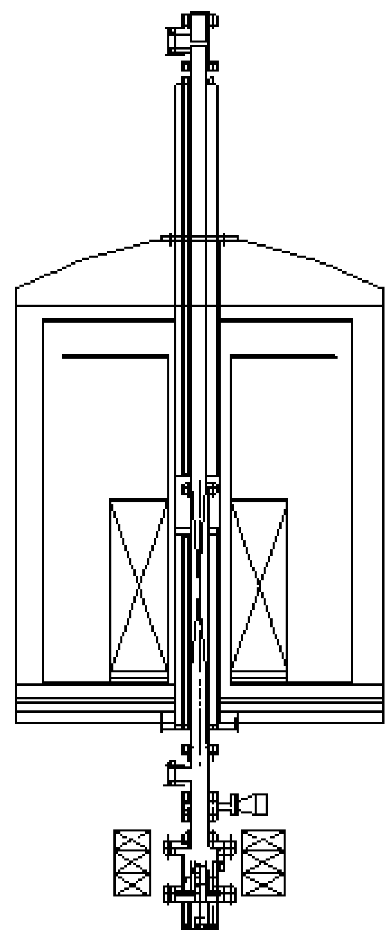

Fig. 1 shows the cross-section of the gyrotron. The gyrotron tube is installed inside an 89 mm bore diameter of 9.2 T superconducting magnet.

Fig. 2 shows the cavity design and the field profile of $TE_{1,6}$ mode. The cavity has the main radius and length of 2.175 mm and 19 mm. Fig. 3 shows the starting currents of the cavity modes at magnetic field ranging from 6.8 to 7.6 T. The beam

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parameters are cathode voltage 15 kV, pitch factor 1.5, and beam radius 0.47 mm. The broken line and solid line denote the fundamental and second harmonics, respectively. It is seen in Fig. 3 that second harmonic mode $TE_{1,6}$ (with f = 394.37 GHz and Q = 13500) is well-isolated from the fundamental ones. It will be used as a source for nearly 600 MH of DNP-NMR experiments. For the fundamental mode, two operating modes: $TE_{4,2}$ (with f = 203.75 GHz and Q = 4600) and $TE_{1,3}$ (with f = 186.97 GHz and Q = 4200) are candidates of millimeter waves sources of DNP-NMR experiment at the frequency nearly 300 MHz.

Fig. 4 shows summary of the multi-mode time-dependent calculation of mode competition. The results were taken from the final stage of time evolution of the RF power (at t = 100 ns) where the main mode $TE_{1,6}$ suppressed other competitors. Then the RF powers are plotted as a function of beam currents at different magnetic fields. Here, beam voltage is 15 kV and pitch factor is 1.5. The gyrotron parameters are summarized in Table I.

The gyrotron is, now, under the operation test. The experimental results will be presented.

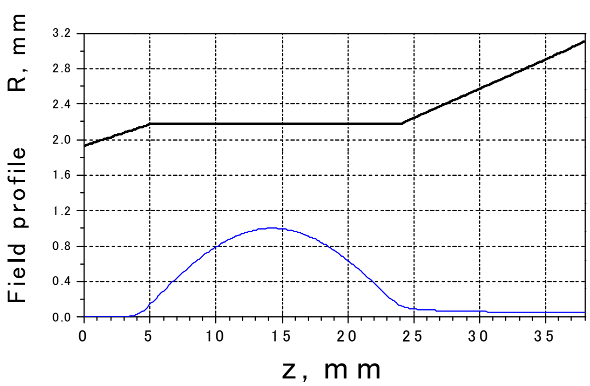

Fig. 2 Cavity design and field profile of main mode $TE_{1,3}$ at second harmonic.

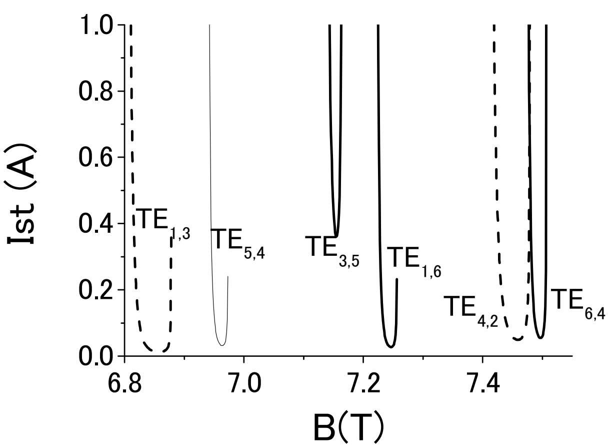

Fig. 3 Plots of starting currents as a function of magnetic field. Here, cathode voltage, beam radius, and pitch factor are 15 kV, 0.47 mm, and 1.5, respectively. Solid line: second harmonic, broken line: fundamental harmonic.

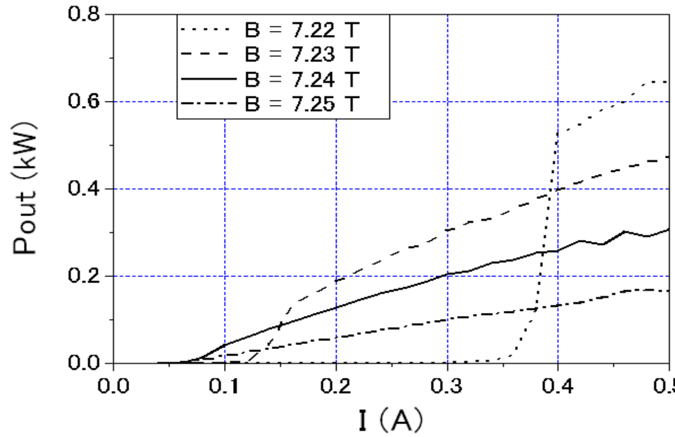

Fig. 4 Calculated output power of $TE_{1,6}$ mode vs. beam current for different magnetic fields (B=7.22, 7.23, 7.24, 7.24 T). Here V_c=15 kV, R_b=0.47 mm, α=1.5.

Table I Summary of gyrotron parameters

Operating mode	$TE_{1,6}$	$TE_{4,2}$	$TE_{1,3}$
Frequency, GHz	394.37	203.75	186.97
Magnetic field, T	7.24	7.45	6.85
Harmonic number	2	1	1
Cavity radius, mm	2.18	2.18	2.18
Cavity length, mm	19	19	19
Quality factor	13499	4620	4227
Beam radius, mm	0.47	0.47	0.47
Magnetic mirror	92	92	92
Beam voltage, kV	15	15	15
Pitch factor	1.5	1.5	1.5
Beam current, mA	200	350	200
Output power, watt	50	200	670

REFERENCES

[1] V. S. Bajaj, et al., "Dynamic nuclear polarization at 9 T using a novel 250 GHz gyrotron microwave source", J. Mag. Res. **160** (2003), 85.

[2] T. Idehara, I. Ogawa, L. Agusu, et al., "Development of 394.6 GHz CW gyrotron (Gyrotron FU CW II) for DNP/proton-NMR at 600 MHz", Int. J. Infrared Millimeter Waves **28** (2007), 443.