High speed frequency modulation of a 460 GHz gyrotron for application to the 700 MHz DNP enhanced NMR spectroscopy

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***Abstract*—The high speed frequency modulation of a 460 GHz Gyrotron FU CW GVI (the official name in Osaka University is Gyrotron FU CW GO-I) was achieved by modulation of acceleration voltage of beam electrons. The modulation speed f_m can be increased up to 10 kHz without decreasing the modulation amplitude δf of frequency. δf was increased almost linearly with the modulation amplitude of acceleration voltage δV_a. At the δV_a=1kV, δf=53 MHz in the case of f_m<10 kHz. The frequency modulation was observed as both the variation of the IF frequency in the heterodyne detection system measured by an oscilloscope and the width of frequency spectrum measured on a frequency spectrum analyzer. Both results well agree reasonably. The experiment was performed successfully for both a sinusoidal wave and a triangle-wave modulations. By using the frequency modulation, we have a possibility to compensate the decreasing of the enhancement factor in high frequency DNP-NMR spectroscopy for example, 700 MHz. In addition, high speed frequency modulation is useful for frequency stabilization by PID control of acceleration voltage by feeding back of fluctuation of the frequency. The frequency stabilization in long time is also important for application of DNP-NMR spectroscopy to analysis of complicated protein molecules.**

I. INTRODUCTION

Recent development of high frequency gyrotrons using high harmonic operations and high field superconducting magnet has achieved the breakthrough of 1 THz operation of the gyrotrons at both short pulse and CW modes. Their high output power can open the developments of high power THz technologies. Among many applications of high frequency gyrations, one of most important technologies is a DNP enhanced NMR spectroscopy. As known well, NMR spectroscopy is an important and useful tool to study on material property. However, its low sensitivity is most severe problem. We can remove this problem by irradiation of high power THz radiation at the Electron Spin Resonance (ESR) condition where huge magnetization of electron spins can be transferred to nuclear spins. In addition, we have already succeeded in the frequency modulation experiment. In this paper, the frequency modulation results using Gyrotron FU CW GVI at the frequency of 460 GHz. This output radiation can be applied for 700 MHz proton DNP-NMR spectroscopy. Rough estimation results on the compensation effect for decreasing of the enhancement factor at the higher frequency are also suggested briefly.

II. RESULTS

First of all, we tried to observe the high-speed modulation of the frequency under the modulation of the acceleration voltage. In Fig. 1 a) and b), the frequency modulations for sinusoidal and triangular wave modulations of the acceleration voltage and in Fig. 2 a) and b) the corresponding frequency spectra observed by a heterodyne system. As seen in the figures, the widths of the frequency spectra are in good agreement with the peak to peak values (the amplitudes) of the frequency modulations.

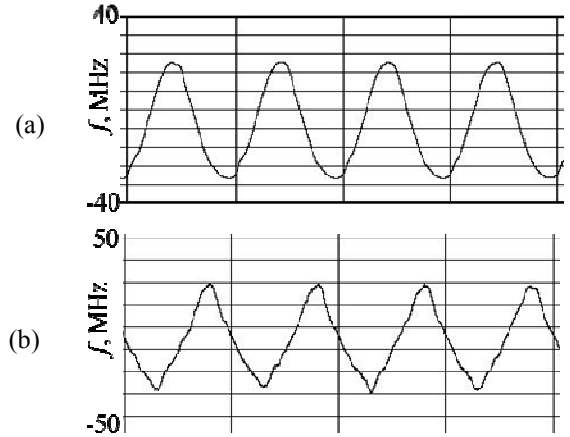

Fig. 1. Frequency versus time. f_m=5 kHz, ΔV_a = 1 kV a) sinusuoidal; b) triangle

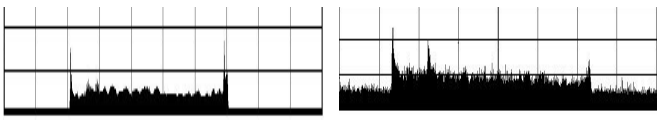

Fig. 2. Frequency spectrum. f_m=10 kHz, ΔV_a =1 kV a) sinusuoidal; b) triangle, 10 MHz/div.

This means that the widths of measured frequency spectra are suitable measures of the amplitude of frequency modulation of gyrotrons. The output power modulation accompany with their frequency modulation. We need the frequency modulation

without any modulation of the amplitude (the output power of gyrotron). Fig 3 shows measured frequency spectra with many modulation amplitudes of cavity potential. We can estimate the amplitudes of frequency modulation of gyrations from the measurement of the widths of measured frequency spectra.
In Fig. 4 , the frequency modulation amplitude be estimated by use of the measurement results of frequency spectra is shown as a function of modulation amplitude of acceleration voltage.

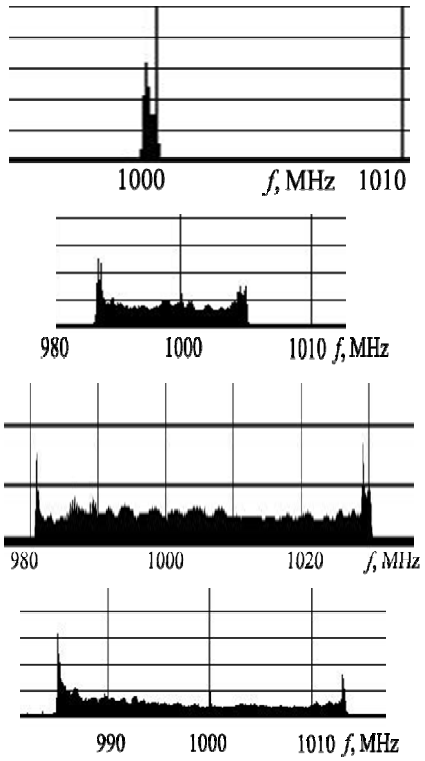

Fig.3 Measured frequency spectra under modulation of acceleration voltage δVa = 0V, 200 V, 1000V and 500 V.

III. SUMMARY

In the real experiment of high frequency 700 MHz DNP-NMR spectroscopy, such a frequency high-speed modulation hopefully will be useful to increase the enhancement factor of NMR spectroscopy significantly.

1) We tried to estimate the modulation amplitude δf of the output frequency from the measurement results of the frequency spectra. Without any modulation on the acceleration voltage, the observed frequency spectrum is a simple feature with the half value width of 0.5 MHz. When acceletation voltage V_a is modulated sinusoidally, the feature of the frequency spectrum is changed to typical feature under sinusoidal modulation. The increase of half value width corresponds to the increase of the modulation amplitude δf.

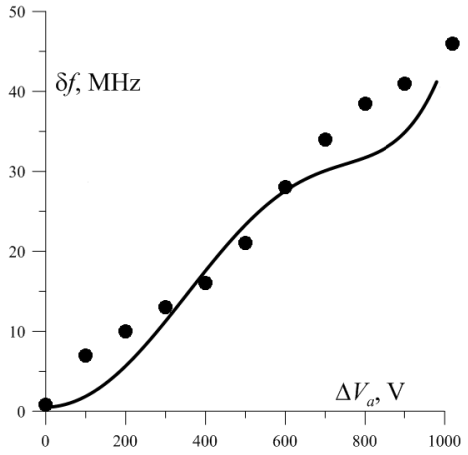

Fig. 4. The amplitude of frequency modulation as function of modulation amplitude of acceleration voltage applied on the body potential. Circle dots: measurement results, Solid line: calculation results using the self consistent calculation system.

2) By changing the acceleration voltage δf, we studied on the dependency of the frequency modulation amplitude δf on the acceletation voltage V_a at the modulation speed f_m of 300 Hz. δf is almost linearly proportional to V_a. The rough calculation results using the same self-consistent calculation system is almost agreement with the measurement result.

3) Finally, we tried high-speed modulation of the frequency by increasing the modulation frequency f_m of acceleration voltage. The amplitude of the resulting frequency modulation is almost constant in the range of f_m<10 kHz. However, if f_m exceeds 20 kHz, the amplitude δf decreased gradually. This is suggesting that the gyrotron operation can follow the changing of the accelation voltage in the case of low frequency modulation. In the case of higher frequncy modulation than a criteria of f_{m0}, the gyrotron operation could not follow the changing of the acceleration voltage.

The gyrotron FU CW GV-I has been already installed of 700 MHz DNP-NMR spectrometer and succeeded in the preliminary experiment and achieved the enhancement factor of around 30 without the frequency modulation. In addition, web have also succeeded in the measurements of two dimensional 700 MHz DNP-NMR spectroscopy, which is strong tool in order to study on the analysis of the structure of complicated protein molecule in high spatial resolution.