CW operation of a Tunable 330/460 GHz gyrotron for enhanced Nuclear Magnetic Resonance

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Abstract*—In this work we describe the operation of a continuous-wave 330/460 GHz gyrotron oscillator operating at the second harmonic of the electron cyclotron frequency. The oscillator is intended to be used in 700 MHz ^{1}H nuclear magnetic resonance (NMR) experiments enhanced by dynamic nuclear polarization (DNP). At 460 GHz, the gyrotron operates in the $TE_{11,2}$ mode and is able to generate 16 W of power continuously and stably for a beam current of 100 mA and beam voltage of 13 kV. Power and frequency tuning measurements as a function of beam voltage and magnetic field were carried out. The results show continuous frequency tunability over a range of 700 MHz with a minimum power level of 5 W for a fixed beam current of 100 mA. Extended frequency tuning due to the interaction of the electron beam with the backward-wave component of successive high order axial modes is observed. Power and frequency tuning measurements are also reported for the $TE_{4,3}$ mode at 330 GHz, a frequency suitable for 500 MHz DNP/NMR spectrometers.

I. Introduction

Dynamic nuclear polarization (DNP) is a technique employed to enhance the signal-to-noise ratio in nuclear magnetic resonance (NMR) experiments and consists of transferring the large polarization of the electron spins to the nuclear spins by irradiating the sample under study with microwaves at a frequency close to the electronic Larmor frequency. High enhancement requires continuous irradiation with a few watts of power in the 140 to 600 GHz range, a task well suited for gyrotron oscillators[1,2]. Gyrotrons operating at the second harmonic of the cyclotron frequency can be used for all NMR frequencies below 800 MHz (proton frequency) while using cheaper NbTi superconducting magnets. The transfer of spin polarization is optimized by tuning either a superconducting sweep coil integrated to an NMR magnet or the frequency of the gyrotron. A tunable gyrotron is highly desirable since it would allow DNP/NMR experiments to be performed without tuning the NMR magnet or with magnets without a superconducting sweep coil. In this work, we describe a continuous-wave 460 GHz gyrotron oscillator operating at the second harmonic of the cyclotron frequency aimed to be used in a 700 MHz DNP/NMR spectrometer. We also report results obtained at a lower magnetic field near 330 GHz, a frequency of interest for 500 MHz DNP/NMR setups. In previous research, we have reported up to 8 W of output power from a 460 GHz gyrotron operating in the TE_{06} mode[3]. The present results were obtained by redesigning[4] and rebuilding the gyrotron to operate at higher output power and efficiency.

II. Design

The gyrotron was designed to operate in the $TE_{11,2}$ mode, a well isolated whispering-gallery mode with good coupling to an electron beam of radius 1.1 mm. The mode is supported by a 30-mm long cylindrical cavity, radius 1.825 mm and interacts with a low voltage (< 15 kV), low current (< 150 mA) electron beam. At 12 kV, the starting oscillation current of the operating mode was computed to be as low as 26 mA. The generated radiation is coupled out of the gyrotron by means of a helical cut launcher and a series of mirrors, and guided to the NMR probe by a low-loss corrugated waveguide.

III. Experimental Results

A. 460 GHz results

The 460 GHz gyrotron has generated 16 W of power in a continuous and stable regime for a beam current I_b = 100 mA and beam voltage V_b = 13 kV. Another feature of interest for DNP/NMR experiments, frequency tuning, was also explored. In gyrotrons, frequency tuning can be achieved by changing the electron cyclotron frequency[3] and/or by perturbing the gyrotron cavity[5]. Considering the former case, power and frequency measurements as a function of beam voltage and magnetic field are presented in Fig. 1 and Fig. 2, respectively. Continuous frequency tunability over a range of 700 MHz with a minimum power level of 5 W was observed for a constant beam current I_b = 100 mA. This represents a continuous frequency tuning range ten times broader than

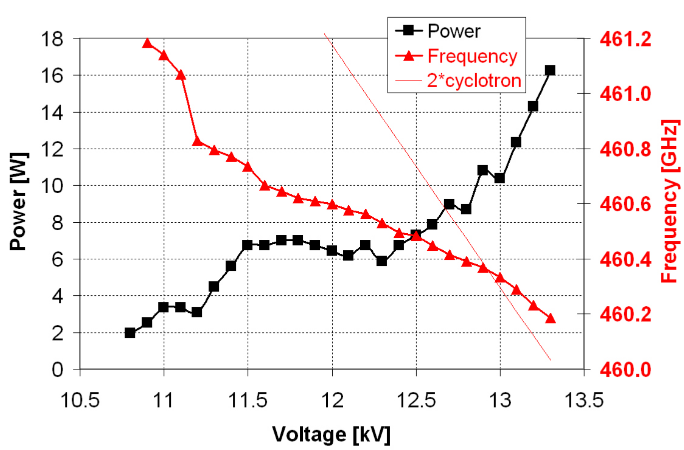

Fig. 1. Power and frequency tuning measurement as a function of beam voltage for the $TE_{11,2}$ mode, beam current I_b = 100 mA, and magnetic field B_0 = 8.431 T.

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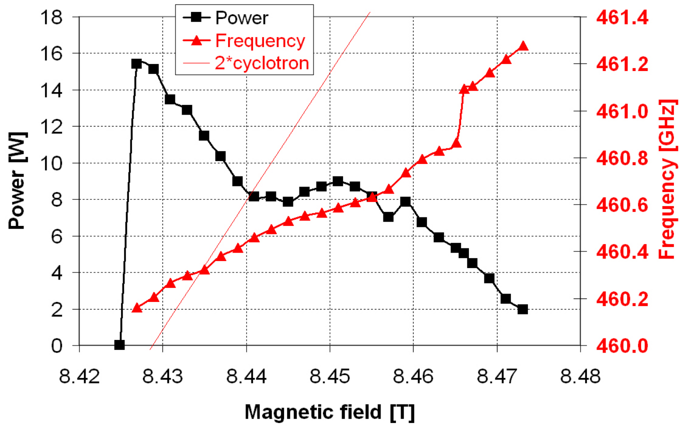

Fig. 2. Power and frequency tuning measurement as a function of magnetic field for the $TE_{11,2}$ mode, beam current I_b = 100 mA, and beam voltage V_b = 13 kV.

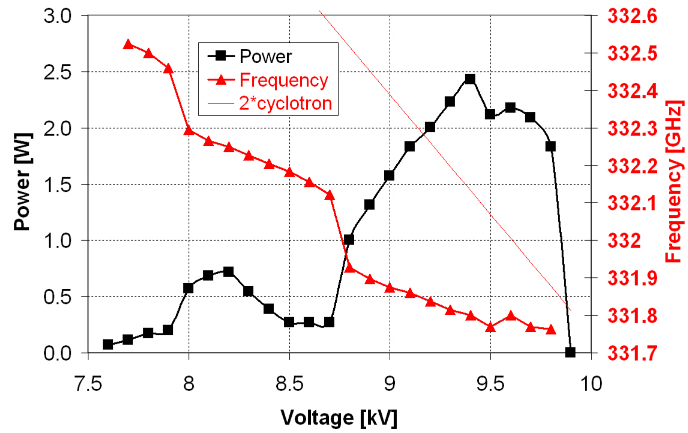

Fig. 3. Power and frequency tuning measurement as a function of beam voltage for the $TE_{4,3}$ mode, beam current I_b = 50 mA, and magnetic field B_0 = 6.042 T.

previously reported[2,3] for a second harmonic mode. Although the minimum measured power of 5 W is suitable for DNP/NMR, a more uniform curve at a higher power level may be expected by increasing the beam current at different voltage and magnetic field values.

As the gyrotron operates in a regime where the axial wavenumber is much smaller than the transverse one, broadband continuous frequency tuning can be achieved by exciting successive high order axial modes since their eigenfrequencies are close to each other, especially in a long gyrotron cavity. As one increases (decreases) the magnetic field (beam voltage), the electron beam interacts with the backward-wave component of a high-order axial mode. This occurs in a region where the radiation frequency is less than the second harmonic of the cyclotron frequency as shown by the red curves in Fig. 1 and Fig. 2. Thermal expansion of the cavity walls with an ideal tuning rate of 7.8 MHz/^{o}C at 460 GHz may be employed to fill tuning curve gaps and to extend the frequency tuning range of the oscillator to over 1 GHz.

B. 330 GHz results

Although the gyrotron was not designed to operate near 330 GHz, 2.5 W of output power could be measured in the $TE_{4,3}$ second-harmonic mode at 332 GHz for a beam voltage V_b = 9.4 kV and beam current I_b = 50 mA. Higher output power would have been achieved by using a proper mode converter and a transparent window at 332 GHz. Power and frequency measurements as a function of beam voltage and magnetic field were also carried out for this mode and the results are shown in Fig. 3 and Fig. 4. Similarly to the 460 GHz case, interaction with the backward-wave component of successive high-order axial modes was observed. This tuning scheme combined with thermal tuning may provide the required tuning range of 1-2 GHz with reasonable power to enable DNP/NMR experiments in 500 MHz NMR spectrometers.

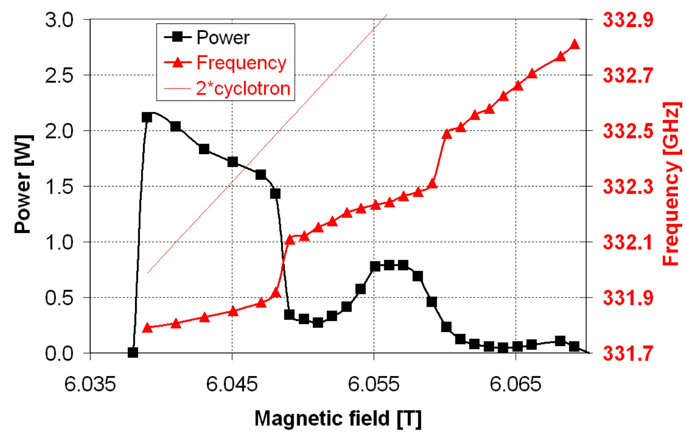

Fig. 4. Power and frequency tuning measurement as a function of magnetic field for the $TE_{4,3}$ mode, beam current I_b = 50 mA, and beam voltage V_b = 9.4 kV.

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