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# Experimental tests of a 263 GHz gyrotron for spectroscopic applications and diagnostics of various media

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A 263 GHz continuous-wave (CW) gyrotron was developed at the IAP RAS for future applications as a microwave power source in Dynamic Nuclear Polarization / Nuclear magnetic resonance (DNP/NMR) spectrometers. A new experimental facility with a computerized control was built to test this and subsequent gyrotrons. We obtained the maximum CW power up to 1 kW in the 15 kV/0.4 A operation regime. The power about 10 W, which is sufficient for many spectroscopic applications, was realized in the low current 14 kV/0.02 A regime. The possibility of frequency tuning by variation of the coolant temperature about 4 MHz/1 °C was demonstrated. The spectral width of the gyrotron radiation was about $10^{-6}$. © *2015 AIP Publishing LLC.* [http://dx.doi.org/10.1063/1.4921322]

## I. INTRODUCTION

The last decade has contributed to the rapid development of THz gyrotrons. The series of continuous-wave (CW) and pulsed tubes have been developed by the Research Center for Development of Far-Infrared Region (FIR-FU) at the University of Fukui (Japan),[1,2] MIT (USA),[3] CRPP-EPFL (Switzerland),[4] and IAP RAS (Russia).[5–7] Some novel applications were proposed, for example, remote detection of concealed radioactive materials,[8] initiation of point-like discharge in a nonuniform gas flow as a source of extreme ultraviolet radiation,[9] and direct measurement of positronium hyperfine splitting.[10] For the work described below, the most relevant application is the high resolution spectrometry.[11] The DNP/NMR spectrometers based on the use of gyrotrons with a relatively high microwave power (several tens of watts) allow to increase the spectrometer signal by two orders of magnitude. The first commercially available gyrotron-based spectrometer was developed by Bruker Biospin that spectrometer utilized the Communications & Power Industries (CPI) gyrotron.[12] A gyrotron with the operating frequency 258 GHz developed by the IAP RAS jointly with GYCOM Ltd. (Nizhny Novgorod, Russia)[13] was successfully used for Dynamic Nuclear Polarization / Nuclear magnetic resonance (DNP/NMR) experiments at the Institute of Physical and Theoretical Chemistry and Center for Biomolecular Magnetic Resonance, Goethe University, Frankfurt am Main, Germany and provided 80-fold signal enhancement.[14] In this paper, we describe a new IAP/GYCOM gyrotron developed for the spectrometry and diagnostics of various media. In contrast to the previous IAP tube, this gyrotron is equipped with the liquid helium-free magnet JSTD 10T100 produced by JASTEC Ltd., which provides the magnetic field up to 10 T in a warm bore with a 100 mm diameter.[15] The gyrotron has an internal mode converter transforming the operating mode into a Gaussian beam. The gyrotron is capable of operation in a wide range of regimes: a high power regime—up to 1 kW at the fundamental cyclotron harmonic with a frequency of 263.1 GHz, as well as a low power regime (about 10 W) with a low operating current (20 mA). The excitation of second harmonic with frequency about 502 GHz and power near 10 W is observed at corresponding magnetic field.

## II. GYROTRON DESIGN

After a careful analysis of the spectrum of cylindrical cavity modes, the $TE_{5,3}$ mode was chosen as the desired one for operation at the fundamental cyclotron resonance. The cavity radius for operation at this mode (R = 2.54 mm) is large enough so that it can be manufactured with high accuracy; the optimal radius of the electron beam is close to $R_b$ = 0.96 mm. The possibility of selective single-mode excitation of this mode without any competition with parasitic modes was confirmed by numerical simulations. The length of the cylindrical part of the cavity was chosen to be 20 mm. Such length allows our gyrotron to operate at low beam currents (tens of mA) so that it delivers the power at the level of several tens of watts and at the same time provides diffractive losses that are much higher than the ohmic losses.

Optimization of the electrodynamic system and calculation of the power and efficiency were carried out by using the self-consistent time-independent codes developed at the IAP RAS.

The gyrotron that was used for experiment has the following characteristics. At the beam voltage 15 kV and current 0.4 A CW, the achievable output power is up to 1 kW. The magnetron injection gun has a $LaB_6$ emitter. The gun has a triode structure, but a simulated nominal operating regime is the diode one (which is more convenient from an operational point of view), i.e., the anode as well as the resonator has

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a ground potential. The magnetic system includes an additional coil in the gun region, making it possible to adjust the parameters of the electron beam. An internal quasi-optical mode converter provides a narrow output wave beam with a Gaussian structure. The mode converter consists of a parabolic mirror and four correcting mirrors. The depth of the corrugated mirror surface is about 0.1 mm which is acceptable for precise manufacturing. The output power is extracted through a boron nitride (BN) vacuum window in the horizontal direction. The window diameter is 32 mm. A spent electron beam is deposited onto the surface of the collector with a conical shape that provides an acceptable thermal loading even in the case of tube misalignments. The gyrotron is manufactured by GYCOM Ltd. The device can operate in both pulsed and CW regimes.

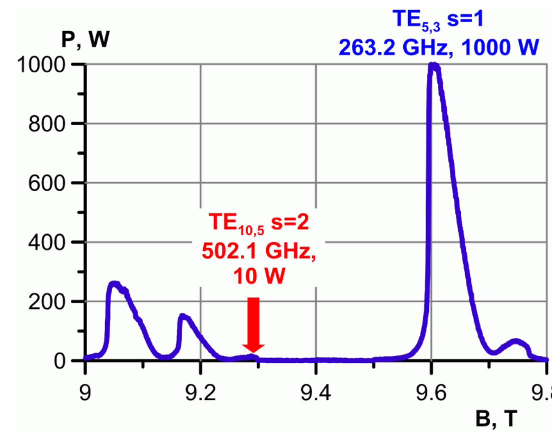


FIG. 1. The dependence of the output power $P$ on the magnetic field $B$.

## III. EXPERIMENTAL DATA

The output power was measured using a dummy load mounted directly after the output window at a beam voltage of 14 kV. Reader can see the dependence of the output power $P$ on the magnetic field (current of the solenoid) at Figure 1. The cathode voltage was 15 kV and the beam current was 0.4 A. The output power reached its maximum value in excess of 1 kW for the magnetic field about 9.605 T. The corresponding efficiency was about 17%. In general, most of the spectroscopic applications require microwave power less than 10 W. Such a low power level (10 W) was realized at a beam voltage of 14 kV and much lower beam current of 0.02 A; this power was obtained with about 3% efficiency.

The described gyrotron had an independent water cooling circuit for the cavity. A chiller with an accuracy of 0.5 °C controlled the temperature of the cooling water. The variation of this temperature affected the cavity radius, thus resulting in the frequency shift. For frequency measurements, a small part of the radiation was picked up through the coupler and forwarded to the harmonic mixer where it was mixed with a highly stable local oscillator signal having the frequency $f_{LO}$. The signal from the mixer at the intermediate frequency $f_{IF}$ was sent to the Rohde & Schwarz spectrum analyzer. Then, the oscillation frequency $f$ was defined as the sum of $nf_{LO} + f_{IF}$, where $n$ was a harmonic number. Fig. 2(a) shows the experimental dependence of the frequency $f$ on the electron beam current $I$ for different values of the beam voltage $U$ and cavity temperature $T$ at a fixed magnetic field B = 9.67 T.

Thus, the frequency variation with the temperature was about 4 MHz/°C, and the frequency variation with the voltage was about 33 MHz/kV. The spectral width $\Delta f$ was about 0.5 MHz ($\Delta f/f \sim 10^{-6}$). Simultaneous variation of the temperature of cavity cooling water and the operating voltage provided 0.2 GHz continuous frequency tuning (Fig. 2(a)). The measured radiation spectrum is shown in Fig. 2(b).

The power at the 10 W level was obtained at the magnetic field about 9.3 T that corresponded to the gyrotron's operation at the $TE_{10,5}$-mode at the second cyclotron harmonic with the frequency 502.1 GHz. It should be noted that the internal mode converter was developed for the $TE_{5,3}$-mode, so after optimization of the mirrors' profiles, the output power at the second harmonic could be slightly increased.

The measurement of the spatial distribution of the microwave power was made in several cross sections by using an

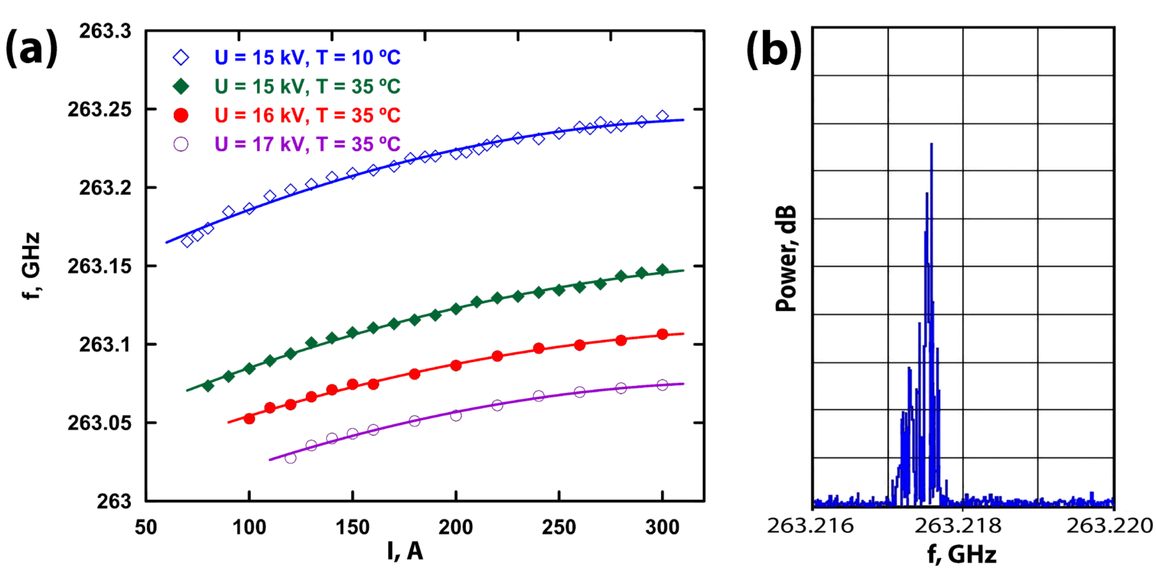


FIG. 2. The frequency tuning map (a) and typical spectrum of gyrotron radiation (b).

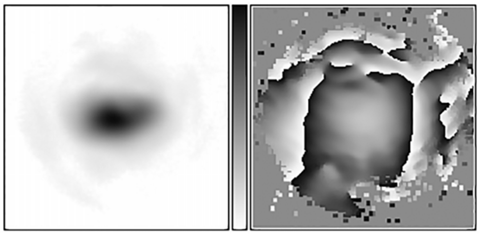

FIG. 3. The measured amplitude and recalculated phase of a microwave beam at the distance Z = 237 mm from the gyrotron window. The $TEM_{00}$ content is 93%.

FIG. 4. A general view of the gyrotron complex.

infrared camera "VarioScan 3021 ST," which had a temperature resolution about 0.03°; so, a dynamic range of the measured data was at least 30 dB. The temperature profile on the dielectric screen corresponded to the distribution of the microwave power passing through the screen.[16] As follows from the measured data, the content of the gaussian-like $TEM_{00}$-mode in the output radiation was 93% (Fig. 3).

## IV. SUMMARY

The developed gyrotron has a record power level and looks promising for many applications. The gyrotron complex shown in Fig. 4 is equipped with a computerized control system (designed to ensure safe operation; collecting, recording, display, and processing of experimental data and technical parameters; remote control of operation regime) which uses an original software. In Fig. 4, the gyrotron inside the cryomagnet and the complex control rack are shown. An interface and interlock systems make such complex user-friendly, so it can be used by a large number of researchers who do not have special experience with microwave tubes and cryomagnets.

The agreement between calculated and experimental data on the power, efficiency, and frequency indicates the correctness of our technological solutions used in the manufacturing process and offers hope that the next versions of the microwave systems operating at frequencies of 527/780 GHz will be successfully implemented. These systems will be based on the second harmonic gyrotrons, which probably will use a multibeam electron optical system (EOS) in order to achieve a better selection of the operating modes.[17]

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