

# CW subterahertz gyrotron operating at high cyclotron harmonics

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**Abstract.** At the IAP RAS, a subterahertz continuous-wave large orbit gyrotron (LOG) operating directly at the second, third, and fourth cyclotron harmonics at frequencies of 0.26, 0.39, and 0.52 THz, is developed and created. The paper presents the results of experimental testing of LOG at the second and third harmonics carried out to date in the long-pulses regime (duration 0.1–60 s) with the transition to continuous-wave generation regime.

## 1. Introduction

At present, at the IAP RAS, LOGs are developing on the base of two experimental setups. The first high harmonic terahertz gyrotron was implemented on the basis of the setup “pulsed LOG” [1]. In the current configuration of this gyrotron, an axial electron beam with a current of up to 0.7 A and a voltage of 50–80 keV is used. In the first experiments, the generation at the second and third cyclotron harmonics with a power of hundreds of watts in a wide (0.55 - 1.0 THz) frequency range with operating magnetic fields of 10-14 T was obtained. The “continuous LOG” setup [2] is being developed as a prototype of a multi-frequency source for spectroscopic applications. It is based on the use of a cryomagnet (5 T) and an axial 30 keV / 0.7A electron beam. The main goal of creating this setup is to obtain continuous generation at the second, third, and fourth cyclotron harmonics at frequencies demanded in NMR spectroscopy of 0.26 - 0.39-0.52 THz with an output power of hundreds of watts. To date, generation at the second and third harmonics in the long-pulse (~ 0.1 s) and CW regimes has been obtained in this gyrotron. To ensure the selective excitation of the fourth cyclotron harmonic as well as to improve the gyrotron operation at the third harmonic, special extended sectioned cavities with reduced diffraction Q-factors of the operating modes are being developed [2, 3].

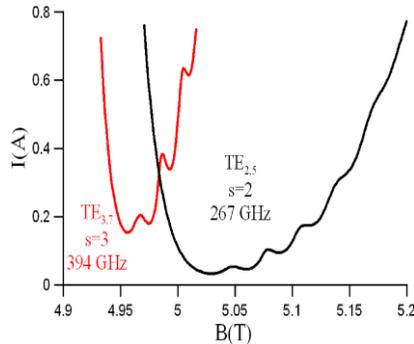
## 2. Experimental study of a continuous-wave LOG

The development of a continuous wave gyrotron with electron beam parameters of 30 keV / 0.7A is aimed at creating a prototype of a universal multi-frequency sub-terahertz source for spectroscopic applications (more specifically, for dynamic polarization of nuclei in

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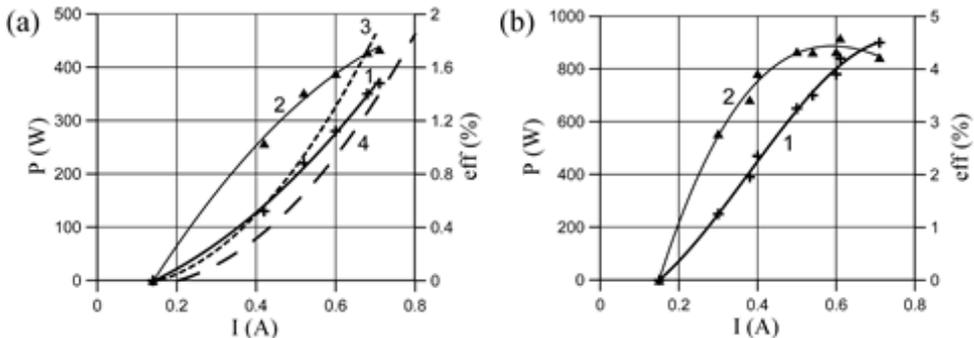
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nuclear magnetic resonance setups). The gyrotron uses a cryomagnet with a magnetic field intensity of about 5 T and an electron-optical system with a magnetic field cusp, which forms an axis-encircling electron beam with an average pitch factor of electrons of 1.5. The main task for this gyrotron setup is to achieve stable and selective generation at the second, third and fourth cyclotron harmonics at attractive frequencies from the point of view of NMR spectroscopy (0.26, 0.39 and 0.52 THz) with an output power of hundreds watts. Further prospects for the development of this LOG are based on increasing the accelerating voltage of particles to 35-45 kV and increasing the operating magnetic field to 6 T. This will make it possible to achieve a fourth harmonic operation at frequency of 0.65 THz which is also demanded from NMR spectroscopy.



**Fig. 1.** Calculated values of the starting currents of modes TE3.7 and TE2.5 at the third and second harmonics, respectively.

In the first experiments, the operation of CW LOG at the second and third cyclotron harmonics was obtained in pulsed regimes (from 10  $\mu$ s to 0.3 s) [2]. Then LOG was tested in long pulse (several seconds) and CW generation regimes. In this case, the same regular cavity (length of 19 mm) was used to excite both the second and third harmonics. The operating modes TE2.5 (second cyclotron harmonic, frequency 0.267 THz) and TE3.7 (third harmonic, frequency 0.394 THz) were excited at slightly different magnetic fields. Numerical simulation predicted a good separation of these two modes by operating magnetic fields (Fig. 1), which was confirmed in experiments [4]. The optimal generation regime at the second cyclotron harmonic was obtained with a magnetic field of 5.02 T, while the third cyclotron harmonic was excited with a field of less than 4.96 T. In long-pulse and CW experiments, a stable “flat” pulse of the output radiation was detected at both harmonics. The maximum generation power at the second / third harmonics was about 800/300 W, which corresponds to an efficiency of about 4% / 1.5% (Fig. 2).



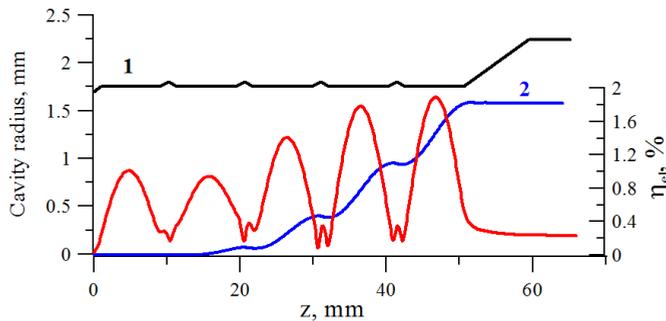
**Fig. 2.** The measured output power (marked + on line 1) and efficiency (triangles on line 2), as well as the calculated output power at a pitch factor of 1.5 (line 3) and 1.4 (line 4) for LOG in the case of second (a) harmonic and third (b) harmonic operation.

### 3. Fourth harmonic CW LOG with quasi-regular cavity

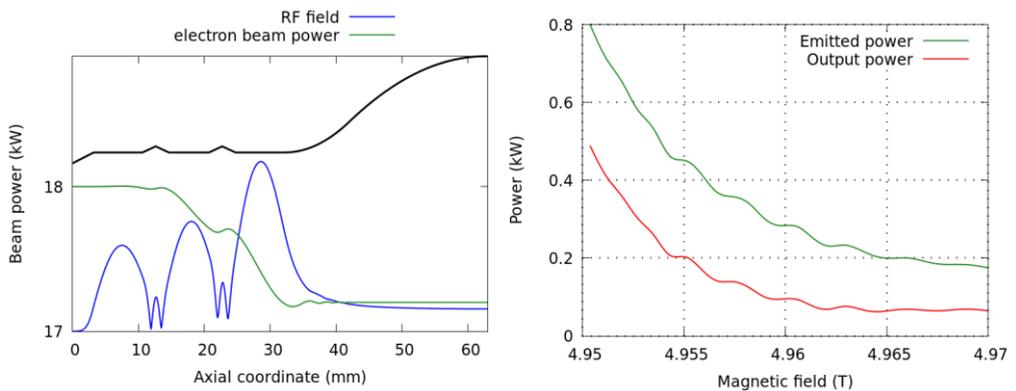
The efficiency of third harmonic operation was low because of is the large (about 70%) share of ohmic losses. This feature is the main obstacle to the transition to fourth cyclotron harmonic operation. In the latter case, the diffraction Q-factor should exceed 100,000, that is, approximately 95% of radiated beam power is lost in the cavity walls. Taking into account the fact that the electron efficiency at the fourth harmonic is also rather low (approximately 2%), the output gyrotron efficiency in such conditions is less than 0.1%.

To improve the third harmonic LOG operation as well as to provide selective fourth-harmonic generation, quasi-regular cavities with periodic phase correctors based on the gyrotron excitation of far-from-cutoff longitudinal modes with relatively low Q-factor [2]. To provide the LOG's fourth harmonic excitation, a cavity consisting of five sections separated by phase correctors was developed and calculated (Fig. 3). In such a cavity, excitation of the operating TE<sub>4.5</sub> mode with five longitudinal variations is expected. Despite the large cavity length (about 90 wavelengths), the diffraction Q-factor of such oscillations is relatively small (~ 30,000). For comparison, the diffraction Q-factor of the lowest longitudinal mode in such a system is about 200,000. Such an approach ensures an acceptable value of the share of ohmic losses (60-70%), which ensures an increase in the gyrotron efficiency at the fourth harmonic from 0.1% (in a regular system) up to 0.5-0.7%.

A similar three-sectioned cavity was also designed to improve the LOG operation at the third cyclotron harmonic (Fig. 4). According to calculations, in this case, the use of sectioning microwave cavity reduces the share of ohmic losses from 65-70% (in a regular system) to about 40%.



**Fig. 3.** A gyrotron with a sectioned cavity at the fourth cyclotron harmonic. The optimized cavity profile (curve 1) and the structure of the high-frequency field of the operating TE<sub>4.5</sub> mode, as well as the calculated dependence of the electronic efficiency on the longitudinal coordinate (curve 2).



**Fig. 4.** A gyrotron with a sectioned resonator at the third cyclotron harmonic. The optimized cavity profile, the structure of the high-frequency field of the operating mode, and the calculated change in the electron beam energy with the longitudinal coordinate (a). Dependences of the power transmitted by the electron beam to the wave, as well as the power of the output radiation from the operating magnetic field (b).

This work was supported by the Russian Science Foundation (Project No. 17-19-01605).

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