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HIGH-HARMONIC GYROTRONS WITH AXIS-ENCIRCLING ELECTRON BEAMS AT IAP RAS

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The Institute of Applied Physics of the Russian Academy of Sciences has for many years been developing sub-terahertz and terahertz large-orbit gyrotrons that permit selective oscillation at higher cyclotron harmonics than is possible in the conventional gyrotrons. Currently, experimental studies are conducted at two specialized facilities. A prototype universal sub-terahertz source for magnetic resonance spectroscopy is studied using a facility that generates long-pulse and continuous electron beams with particle energies of up to 30 KeV. Continuous selective oscillation at the second and third cyclotron harmonics with frequencies of 0.267 and 0.394 THz was obtained for a radiation power of 900 and 370 W, respectively. New resonators with periodic phase correctors have been developed to increase the efficiency of third-harmonic oscillation and obtain fourth-harmonic oscillation with frequencies of up to 0.65 THz. Using a facility with an electron energy of up to 80 KeV, we study the possibilities of increasing the pulse generation power at the third harmonic at frequencies close to 1 THz to employ in experiments on obtaining a gas discharge in a focused terahertz wave beam and generating high-power extreme ultraviolet radiation.

1. INTRODUCTION

The gyrotron is the best known and developed variety of cyclotron masers based on the selective excitation of quasi-critical modes of the waveguide resonators by moderately relativistic electron beams. Relatively low accelerating voltages and relatively weak restrictions on the spread of the electron beam parameters, which are sufficient to create highly efficient oscillators with power inaccessible to other sources, make gyrotrons one of the most attractive radiation sources in the millimeter and submillimeter wavelength ranges. The main factor limiting the advancement of gyrotrons into the terahertz frequency range is the need to use strong magnetic fields. The cryomagnets currently available for gyrotrons provide magnetic fields of up to 10–15 T, which corresponds to electron cyclotron frequencies 0.3–0.4 THz. This means that to achieve higher frequencies in long-pulse and continuous-wave gyrotrons it is necessary to operate at high cyclotron harmonics. Herein, as a rule, in high-frequency conventional gyrotrons it is possible to obtain selective oscillation with a significant radiation power only at the fundamental and second harmonics [1–8]. The main obstacle to using higher harmonics for weakly relativistic electron energies is rapid attenuation of the efficiency of electron–wave interaction with increasing harmonic number and spurious excitation of lower harmonics.

A well-known method of mastering higher harmonics is to use, instead of the conventional gyrotrons, the so-called large-orbit gyrotrons (LOGs) [9-17]. This approach uses, instead of the tubular electron

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beams, axis-encircling beams, in which the particles move along helical trajectories encompassing the axis of a circular resonator. This configuration significantly increases the selectivity of high harmonic excitation, since the axis-encircling beam can mainly excite only the modes with azimuthal indices m coinciding with the number s of the resonant cyclotron harmonic. Moreover, the axis-encircling configuration of the electron beam is optimal in terms of the efficiciency of electron–wave interaction at high harmonics.

In the first LOG of a frequency range above 0.2 THz studied at the IAP RAS, the axis-encircling electron beam was generated by using a quasi-Pierce gun with magnetically guided particles and a high degree of beam compression (by a factor of 4400). The axis-encircling beam generated in this system had a high particle energy of 250 keV, a current of 3 A, and a duration of 10 μs. Using this beam, single-frequency oscillation was obtained at the third cyclotron harmonic in a gyrotron with two different resonators at the $\mathrm{TE}_{3,5,1}$, $\mathrm{TE}_{3,8,1}$, and $\mathrm{TE}_{3,9,1}$ modes in the frequency range 0.37–0.41 THz with a power of 10 to 20 kW [15].

Currently, the high-harmonics LOGs developed at the IAP RAS use considerably lower accelerating voltages. The next gyrotron at a high cyclotron harmonic was based on the “pulsed LOG” with an accelerating voltage of up to 80 kV [17] (see Fig. 1*a*). This gyrotron uses an axis-encircling electron beam generated by a gun with reversed (cusped) magnetic field, a current of up to 0.7 A, and a voltage of 50–80 kV. In the first experiments, we obtained selective oscillation at the second and third harmonics with power at a level of 0.3–2.0 kW over a wide frequency range 0.55–1.00 THz for magnetic fields of 10–14 T. Various new schemes of irregular resonators have been tested to increase the output radiation power of this LOG to a few kilowatts at frequencies of about 1 THz. An oscillator with such parameters is in demand for obtaining a terahertz discharge in a gas.

The “continuous-wave LOG” [16] (see Fig. 1*b*) was developed as a prototype multifrequency source for spectroscopic applications. It is based on the use of a cryomagnet with a field of up to 5 T and an axis-encircling beam with a particle energy of up to 30 keV and a current of up to 0.7 A. The main objective of the creation of this setup is to obtain continuous-wave oscillation at the second, third, and fourth harmonics at frequencies of 0.26, 0.39, and 0.52 THz, which are most in demand for the dynamical polarization of nuclei in the nuclear magnetic resonance (NMR) spectroscopy, with output radiation power at a level of hundreds of watts. By now, oscillation at the second and third harmonics in the long-pulse [16] and continuous-wave [18] regimes has been obtained in this gyrotron. For providing selective excitation of the fourth cyclotron harmonic, as well as for increasing the operation efficiency at the third harmonic, special extended sectioned resonators with reduced diffraction Q-factors of the operating modes are created.

2. PULSED LARGE-ORBIT GYROTRON

In the original version of a pulsed LOG, the electron–optical system with a magnetic field cusp and the subsequent drift of particles in the increasing magnetic field with a high compression factor (3000) generates an electron beam with a current of up to 0.7 A and an acceptable velocity and position spread in a wide range of accelerating voltages (50–80 keV) and magnetic fields (10–14 T). The system operates in pulsed regime with a pulse duration of the order of 10 μs and a repetition rate of up to 0.1 Hz. In the first experiment [17], single-mode oscillation was obtained at the second and third cyclotron harmonics at four frequencies lying in a wide (0.55–1.00 THz) frequency range. The output radiation power at the second harmonic at frequencies of 0.55 and 0.68 THz was 0.6 and 2.0 kW, respectively, while during oscillation at the third harmonic at frequencies of 0.87 and 1.0 THz corresponding to the excitation of the $\mathrm{TE}_{3,6}$ and $\mathrm{TE}_{3,7}$ modes, the radiation power was equal to 0.3–0.4 kW.

Research based on this facility has recently been performed to increase the power of the pulsed LOG operating at the third harmonic with a frequency of about 1 THz to create a source of extreme ultraviolet radiation obtained on the basis of a gas discharge in the focused terahertz wave beam. It should be noted that earlier this LOG has already been successfully employed in similar experiments [19, 20], in which, however, the second cyclotron harmonic oscillation with a radiation frequency of 0.55 THz and a power of 1 kW was used. At the same time, experiments [21] and theoretical calculations showed that for a better matching of the heating radiation with plasma [22] and increasing the degree of conversion of the terahertz radiation

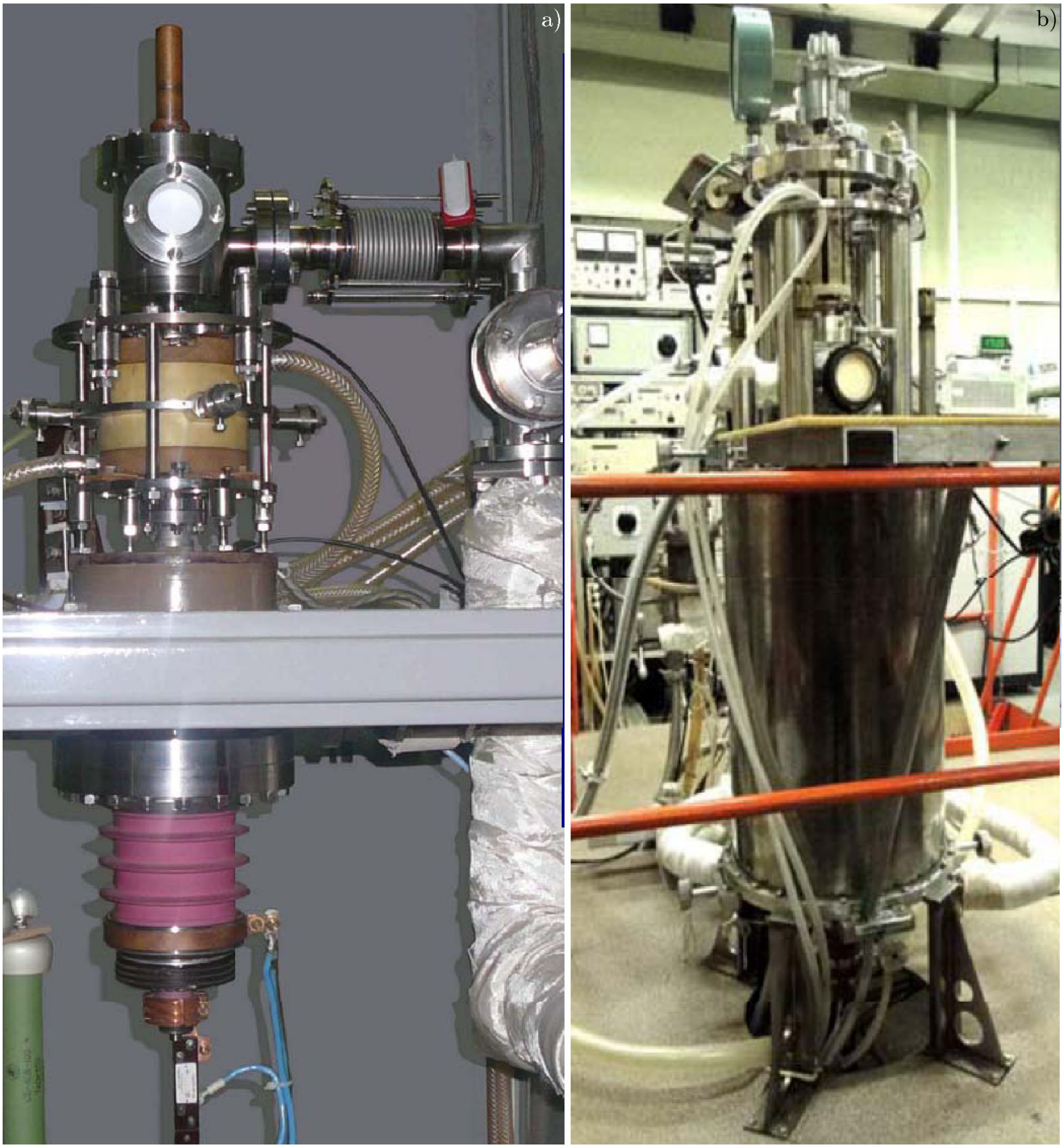

Fig. 1. Pulsed (*a*) and continuous-wave (*b*) large-orbit gyrotrons at high cyclotron harmonics studied at the IAP RAS.

into extreme ultraviolet radiation [23] it is necessary to increase the frequency of terahertz radiation by at least up to 1 THz, while maintaining a kilowatt power level. Moreover, experiments showed that to extend the range of gas pressures in which the discharge exists, it is necessary to increase the gyrotron power. Moreover, in the case of a sufficiently strong focusing of the terahertz beam at a higher frequency it is possible to significantly increase the specific energy input into the plasma, which will lead, in particular, to an increase in its radiance in vacuum and extreme ultraviolet ranges. According to estimates, at a frequency of 1 THz and a power of a few kilowatts, one can hope to obtain a radiation power of up to 100 W in the requested wavelength range 13–17 nm.

According to estimates, a significant increase in the LOG radiation power at a frequency of 1 THz from the achieved value 400 W to a few kilowatts can be obtained with the existing parameters of the electron beam 80 keV and 0.7 A due to only a modification of the conventional resonator, leading to a decrease in its ohmic losses. The fact is that a relatively low power of the LOG with a conventional resonator operating at the third harmonic and the corresponding relatively low efficiency about 1% are a consequence of the weak electron–wave interaction at a high harmonic and a relatively low current of the electron beam. It appears that self-excitation of the operating oscillation in this case requires a fairly long gyrotron resonator with a length of 24 wavelengths, having a diffraction Q-factor of more than 20000, which significantly exceeds the ohmic Q-factor of the resonator and leads to large radiation losses. Calculation for such a system gives a relatively high efficiency of extraction of the electron beam energy by the wave (electron efficiency) equal to about 10%; however, the output efficiency (ratio between the output radiation power and the electron beam power) is only 1.5% [14], according to calculations. This corresponds to that 85% of the power emitted by the electrons into the operating wave is lost due to ohmic losses. In such a situation, a decrease in the fraction of ohmic losses, for example, by two times, could lead to an increase in output radiation power by almost four times.

One of the possible methods leading to a power increase is the use of various irregular resonator circuits with improved efficiency of electron–wave interaction and reduced ohmic losses. In particular, it was shown in [14] that the use of a sectioned resonator in the gyrotron described above can increase the output efficiency by up to 5%, which corresponds to a generation power of more than 2 kW. The possibility of a significant reduction in ohmic losses in a LOG with such a resonator was demonstrated in a model experiment [24].

To further increase the generation power, it is assumed to increase the voltage and current of the beam from 80 kV and 0.7 A to 100 kV and 1.2 A, which will double the beam power. According to calculations of the electron–optical system, it is possible to significantly improve the quality of the electron beam by halving the transverse velocity spread and increasing the electron pitch factor in the operating resonator from 1.4–1.5 to 1.7–1.8. Since the starting and operating currents of the gyrotron at the third cyclotron harmonic are inversely proportional to the sixth degree of the transverse velocity, a corresponding increase in the transverse velocity of particles increases drastically the efficiency of electron–wave interaction. Numerical simulation shows that this gives not only an increase in the electron–wave interaction efficiency from about 10% to 20%, but, which is much more important, a significant reduction in the required resonator length by about 1.5 times and, accordingly, a considerable decrease in ohmic losses from 85% to 50%. Estimates show that with such a beam, even when using a simple regular gyrotron resonator the LOG power can be 3–4 kW.

3. LARGE-ORBIT CONTINUOUS-WAVE GYROTRON

The development of a continuous-wave LOG with electron beam parameters 30 keV and 0.7 A aims at creating a prototype universal multifrequency sub-terahertz source for spectroscopic applications (more specifically, for dynamic polarization of nuclei in NMR facilities). The LOG under study uses a cryomagnet with a field of about 5 T and an electron–optical system with a magnetic field cusp, which generates an axis-encircling electron beam with a mean particle pitch factor of 1.5 in the operating resonator. The main objective for this facility is to achieve stable and selective oscillation at the second, third, and fourth cyclotron harmonics at frequencies of 0.26, 0.39, and 0.52 THz, respectively, which are attractive from the point of view of NMR spectroscopy, for an output radiation power level of hundreds of watts. The further prospects for improving this LOG are based on an increase in accelerating voltage of particles to 45 kV and raising the operating magnetic field to 6.3 T. This will give an opportunity to achieve a frequency of 0.65 THz at the fourth harmonic, which is already in demand in NMR spectroscopy.

In the first experiments, the operation of a continuous-wave LOG at the second and third cyclotron harmonics was tested in pulsed regimes with pulse durations of 10 μs and 0.1 s [16]. Then, the LOG was examined in long-pulse regimes with pulse durations from 0.1 s to 1 min and, finally, put into continuous-wave oscillation [18]. The same regular resonator with a length of 19 mm was used to excite the second and third harmonics. The modes $\mathrm{TE}_{2,5}$ with a frequency of 0.267 THz at the second harmonic and $\mathrm{TE}_{3,7}$

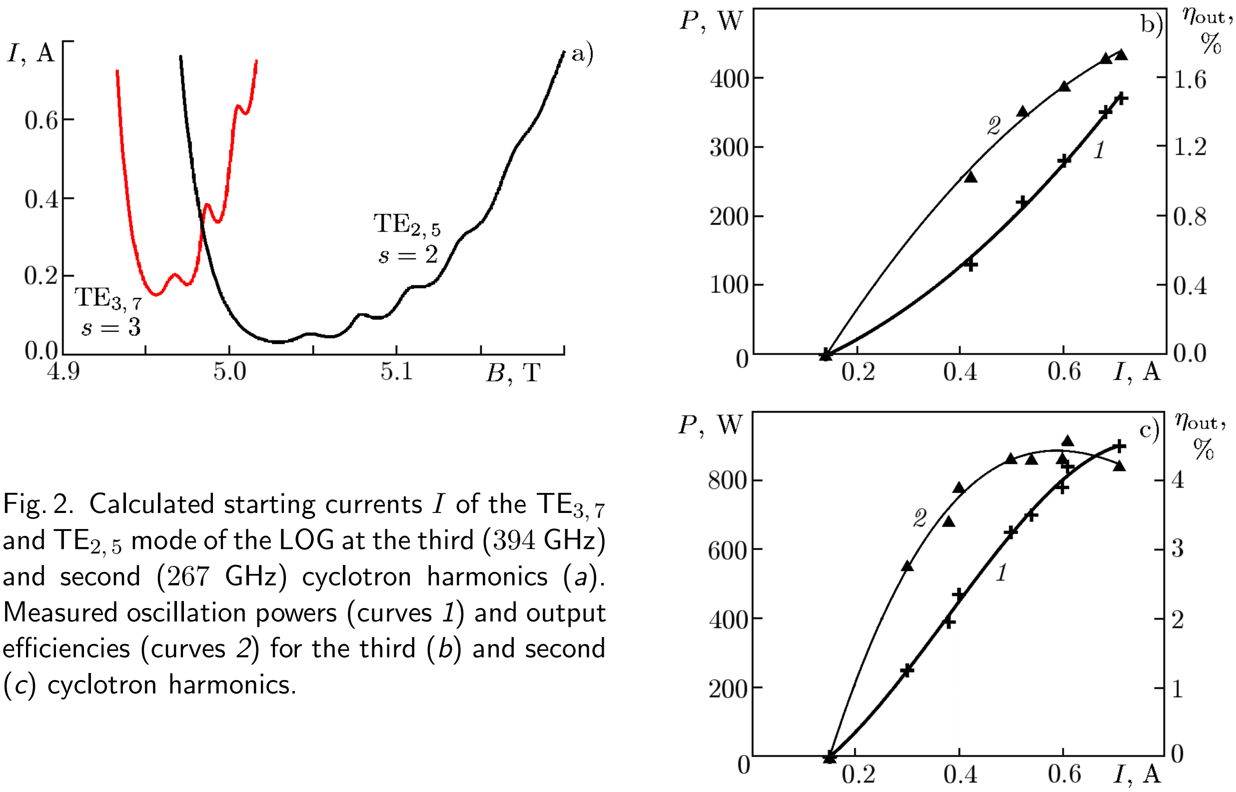

Fig. 2. Calculated starting currents I of the TE$_{3,7}$ and TE$_{2,5}$ mode of the LOG at the third (394 GHz) and second (267 GHz) cyclotron harmonics (*a*). Measured oscillation powers (curves *1*) and output efficiencies (curves *2*) for the third (*b*) and second (*c*) cyclotron harmonics.

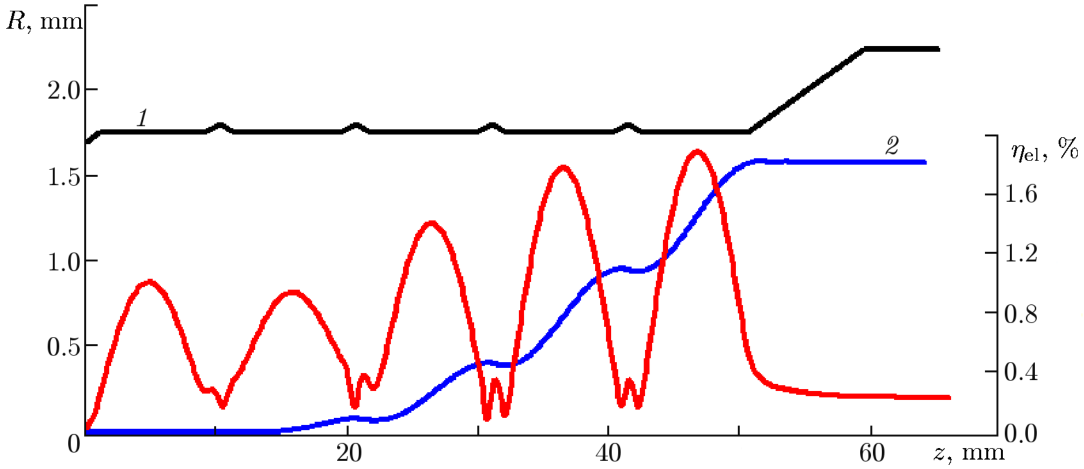

Fig. 3. Gyrotron with a sectioned resonator at the fourth cyclotron harmonic. Optimized resonator profile $R(z)$ (curve *1*), longitudinal field structure of the operating TE$_{4,5}$ mode (red curve) and calculated dependence of the electron efficiency on the longitudinal coordinate (curve *2*).

with a frequency of 0.394 THz at the third harmonic, according to calculations, were separately excited with slightly differing magnetic fields (see Fig. 2*a*). The optimal oscillation regime at the second harmonic was observed for a field of 5.03 T, while the third harmonic was excited for fields less than 4.95 T. In long-pulse and continuous-wave regimes, a stable output-radiation pulse with a flat top was detected at both harmonics. The maximum powers were about 900 and 370 W for an efficiency of about 4.2% and 1.7% at the second and third harmonics, respectively (see Figs. 2*b* and 2*c*).

The low oscillation efficiency at the third harmonic and in this LOG is to a considerable degree due to a large (about 70%) fraction of ohmic losses. The same factor is the main obstacle for operation at the fourth harmonic, since in this case, a resonator with length greater than 60 wavelengths and ohmic loss fraction greater than 90% is required. Accordingly, numerical simulation predicts low values of the power

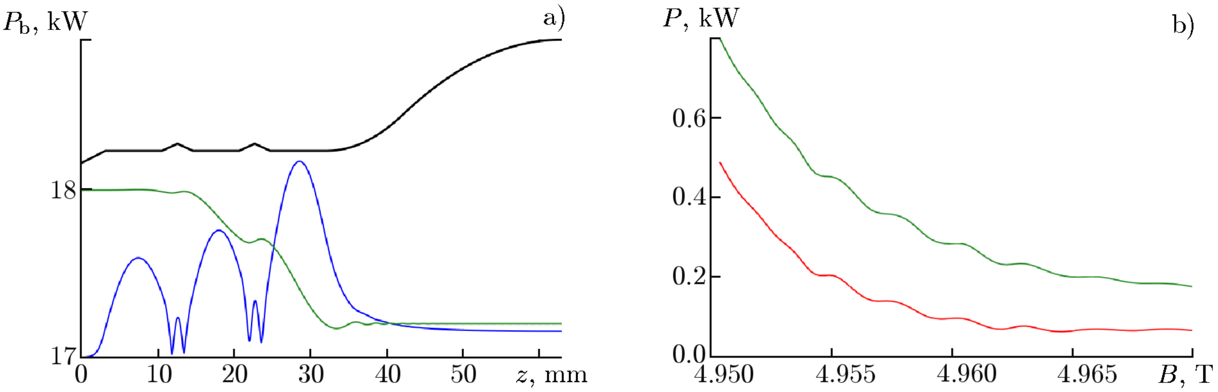

Fig. 4. Gyrotron with a sectioned resonator at the third cyclotron harmonic. Panel *a*: optimized resonator profile (black line), longitudinal field structure of the operating mode (blue line), and calculated variation in the electron beam energy with a longitudinal coordinate (green line). Panel *b*: dependences of the power delivered by the electron beam to the wave (green line) and output radiation power (red line) on the magnetic field.

and efficiency, 35 W and 0.1%, for the fourth harmonic [16].

To increase the operation efficiency at the third harmonic, as well as for oscillation at the fourth harmonic, we developed quasi-regular resonators with periodic phase correctors based on gyrotron excitation far from cutoff and, therefore, having a low diffraction Q-factor of longitudinal modes [25, 26]. A resonator comprising five sections separated by phase correctors (see Fig. 3) was developed for the LOG operating at the fourth harmonic. Such a resonator is expected to excite the operating mode $\mathrm{TE}_{4,5}$ with diffraction Q-factor close to the Q-factor of the fifth longitudinal mode $\mathrm{TE}_{4,5,5}$ of a regular resonator. Although the calculated resonator length is very large (about 90 wavelengths), this Q-factor is relatively low (about 30000). For comparison, the diffraction Q-factor of the lower longitudinal mode in such a system is about 200000. This method provides an acceptable value of ohmic losses, 60–70%, and an increase in LOG efficiency at the fourth harmonic from 0.1% in a regular system to 0.5–0.7%.

A similar, but three-section resonator is also designed to increase the LOG efficiency at the third harmonic (see Fig. 4). According to calculations, in this case the use of sectioning reduces the ohmic loss fraction from 65–70% in a regular system up to approximately 40%.

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