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Terahertz-frequency-range large-orbit-gyrotrons for physical applications

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Abstract

We describe high-harmonic gyrotrons with axis-encircling electron beams developing on the basis of two experimental setups. The 30 keV / 0.7 A CW gyrotron is developed for the spectroscopy applications. Recently, selective operation at the second (0.267 THz) and at the third (0.394 THz) cyclotron harmonics were achieved. Special quasi-regular cavities are designed to to achieve the fourth-harmonic operation at frequencies of up to 0.65 THz. The pulsed 80-100 keV / 0.7-1.0 A gyrotron is aimed to provide high-power microwave pulses at the third cyclotron harmonic at frequencies close to 1 THz. Now we study possibilities to increase the peak level of the output power up to the level of several kW in order to use this gyrotron in plasma applications.

1 Introduction

The conventional gyrotrons operating in the THz frequency range require very strong magnetic fields. The fields can be decreased by using high-cyclotron-harmonic operation of the gyrotron performed in the configuration of the large-orbit gyrotron (LOG) with an axis-encircling electron beam. This configuration improves both the electron-wave coupling and the mode selectivity significantly.

Two terahertz LOG installations are being developed at the IAP RAS for various physical applications [1]. In the ”pulsed LOG” installation, an electron-optical system with a cusp gun provides the formation of a 0.7 A electron beam at 50-80 keV voltages and 10-14 T magnetic fields. In the first experiment [2], operation was achieved at the second and third cyclotron harmonics in a wide (0.55 - 1.0 THz) frequency range. Now, the main activity at this setup is concentrated on studying the possibility to increase the electron beam power up to 100 keV / 1 A in order to achieve the power level of several kW at a frequency close to 1 THz. These parameters seems attractive for some plasma applications.

The next our step in LOG development is aimed to creation of a 30 keV/0.7A continous-wave (CW) gyrotron [1]. The setup is based on a 5 T cryomagnet and a cusp gun forming electron beam with a pitch-factor of 1.5. The main scope is to provide gyrotron operation at the second-third-fourth cyclotron harmonics at the frequencies 0.26 THz, 0.39 THz, and 0.52 THz, respectively, with the output power level of hundreds of Watts for DNP/NMR applications. Recently [3], this setup was tested in a number of long-pulse (~0.1 s) and CW experiments. The selective excitation of the second and third cyclotron harmonics at slightly different magnetic fields was observed. A special long sectioned cavity with decreased Ohmic losses is designed to provide selective excitation of the fourth cyclotron harmonic at a frequency close to 0.5 THz.

2 Pulsed LOG system for plasma applications

In this installation (Fig. 1), an electron-optical system with a cusp gun and a subsequent drift section of adiabatic magnetic compression with a record factor of 3,000 provides the formation of a 0.7 A beam of gyrating electrons. The system operates in the pulsed (~10 μs) regime. According to simulations, the operating electron beam possesses admissible velocity and position spreads in a wide range of voltages (50-80 keV) and magnetic fields (10-14 T).

In the first experiment [2], single-mode operation was achieved at the second and third cyclotron harmonics at four frequencies in a wide (0.55 - 1.0 THz) frequency range. The output power of about 0.3 and 0.4 kW was observed in the third-cyclotron-harmonic regime at the frequencies of 0.87 and of 1 THz (the operating transverse modes are $TE_{3,6}$ and $TE_{3,7}$, respectively) with an output efficiency of ~1%. A relatively low efficiency of the third-harmonic operation in this gyrotron was caused by weak electron-wave coupling at the high-cyclotron harmonic, as well as a relatively low electron current of the axis-encircling beam. As a result, a long-length (24 wavelengths) operating cavity with a very high diffraction Q-factor was used so that a great share of the radiated rf power was dissipated due to ohmic losses. Simulations predicted a quite high (10%) total electron efficiency; however, the ohmic losses decrease the output efficiency down to 1.5% [3]. In order to combine a long-length interaction region and a relatively low diffraction Q factor, a sectioned system with decreased Ohmic losses was designed [4]. In the experiment [5], selective excitation at the third-harmonic operation was achieved. The share of the ohmic losses in this experiment was lower (20%–25% of the rf wave power emitted from the electron beam) as compared to the first experiment [2], where the losses were as high as 85%.

Now we study possibilities to increase the output power at frequencies close to 1 THz up to the level of several kW. This seems attractive for the use of this rf signal in some plasma applications. In particular, such a signal can be used to provide a THz plasma discharge in a gas media; this can be a point-like source of a powerful UV radiation. The increase in the power should be ensured by the simultaneous use of two approaches, namely (i) unceasing the power of the operating electron beam up to 100 keV / 1 A and (ii) using irregular operating cavities with decreased Ohmic losses [6,7]. Figure 2 illustrates results of numerical simulations demonstrating the possibility to achieve the output power at the level of 4 kW in the simple regular operating cavity. An acceptable selectivity of the third-harmonic operation is provided by the increased radial index of the operating mode ($TE_{3,9}$ instead of $TE_{3,7}$ in the earlier experiment [2]). Note that a small admixture of the parasiti second-harmonic wave $TE_{2,6}$ still presents in the output signal; however, this seems not important from the point of view of the use of such THz signal to provide a THz plasma discharge.

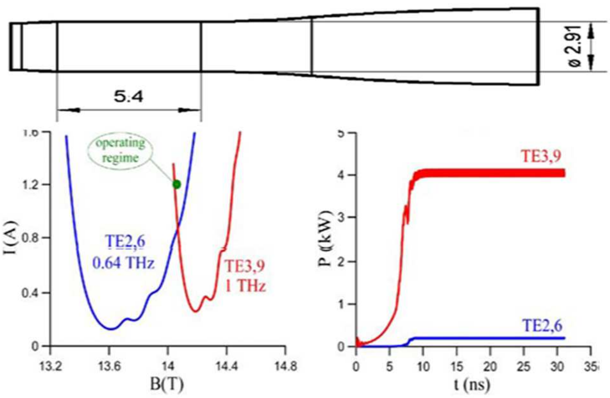

Figure 1. Simulations of the 1 THz third-harmonic gyrotron. The shape of the operating cavity, starting currents of the operating (red curve) and main parasitic (blue curve), and the output powers of these modes versus the time.

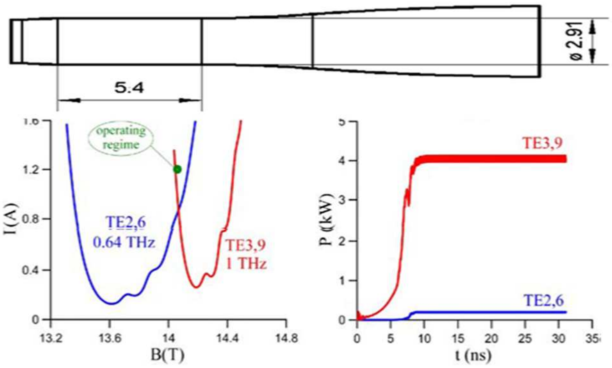

Figure 2. Simulationf of the 1 THz third-harmonic gyrotron. The shape of the operating cavity, starting currents of the operating (red curve) and main parasitic (blue curve), and the output powers of these modes versus the time.

3 CW LOG system for spectroscopy applications

Development of the 30 keV/0.7A gyrotron is aimed at the development of a CW source operating being attractive for DNP/NMR applications. The "CW LOG" setup (Fig. 3) is based on the use of a 5 T cryomagnet and a cusp gun forming axis-encircling electron beam with a pitch-factor of 1.5 [1]. The main scope of this setup is to provide gyrotron operation at the second, third, and fourth cyclotron harmonics at the frequencies 0.26 THz, 0.39 THz, and 0.52 THz, respectively, with the output power level of hundreds of Watts. The further development of the CW LOG installation is related with increasing the electron beam voltage up to 45 keV together with increasing the magnetic field up to 6.3 T. In thic situation, according to theoretical calculations, the operation at promising frequencies of 0.585 THz and 0.65 THz is also possible. This way can offer convenient and much more accessible generators for DNP-NMR spectroscopy and other applications, as compared to other devices. Actually, the same universal installation is to provide generation within a wide frequency range of 0.26-0.65 THz at several frequencies being important from the point of view of the DNP/NMR applications.

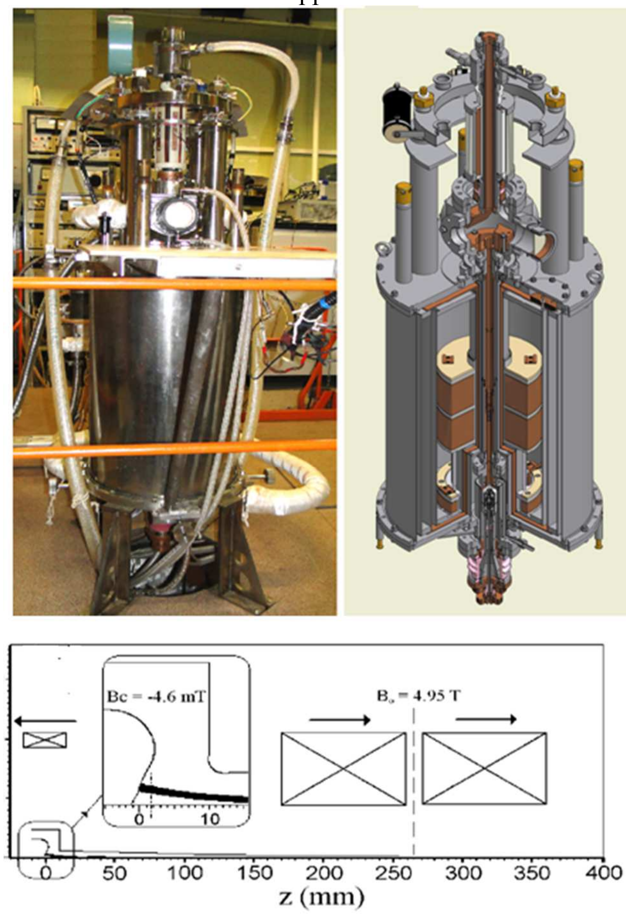

Figure 3. CW large-orbit gyrotron. Photo and schematic of the installation, as well as the electron-optic system.

In first experiments, the "CW LOG" setup was tested in pulsed (from 10 μs up to 0.3 s) experiments [1]. In the second series of experiments, this LOG was tested in the long-pulse (several seconds) regime, and, then, it was put in the CW regime [3]. The same regular cavity with the length of 19 mm was used to provide selective excitation of the mode $TE_{2,5}$ at the second cyclotron harmonic (0.267 THz) and of the mode $TE_{3,7}$ at the third harmonic (0.394 THz) at slightly different magnetic fields. The experiments demonstrated a good separation of these two modes (Fig. 4). The optimal regime of the second-harmonic generation was observed at the field B=5.02 T, when a quite flat rf pulse with a power of ~ 800 W was observed. At a lower (B=4.93 T) field, the third-harmonic pulse with a power of ~ 300 W was registered.

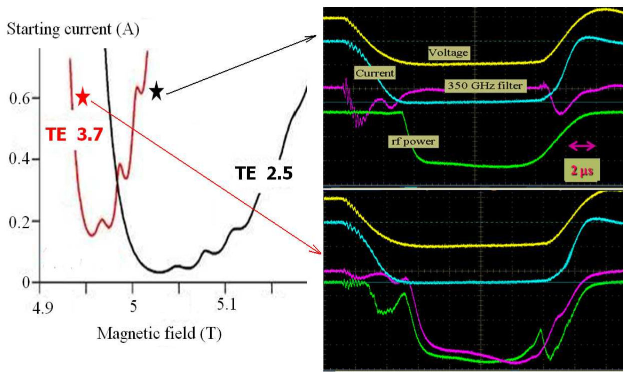

Figure 4. Starting currents versus the magnetic field for the third-harmonic wave TE 3,7 and the second-harmonic wave TE 2,5. Oscilloscope traces of the voltage, current, rf power signal, and the rf power signal passed through a 350 GHz filter in regimes of the second-harmonic and the third-harmonic operation.

In order to provide operation at the fourth cyclotron harmonic at a frequency of 0.52 THz with the power level of ~ 100 W, special cavities with a decreased diffraction Q-factors are required (Fig. 5). Actually, the 0.52 THz CW fourth-harmonic gyrotron requires a long (50-60 wavelengths) operating cavity, so that the diffraction Q-factor of the lowest axial mode (over 100,000) is much greater than the Ohmic Q-factor (~10,000), and the share of Ohmic losses is over 90%. At the electron efficiency ~ 2% this leads to a very low (0.1%) output efficiency. We designed an irregular cavity based on the gyrotron-type excitation of a far-from-cutoff axial mode [6,7]. This is a cavity consisting of 5 sections (separated by special phase correctors) and based on the excitation of the mode $TE_{4,5}$ with 5 axial variations. Sectioning makes possible to reduce the diffraction Q-factor of the operating wave down to ~30,000, and to reduce the share of Ohmic losses down to 60-70%. The latter increases the output wave efficiency from 0.1% up to 0.5-0.7%.

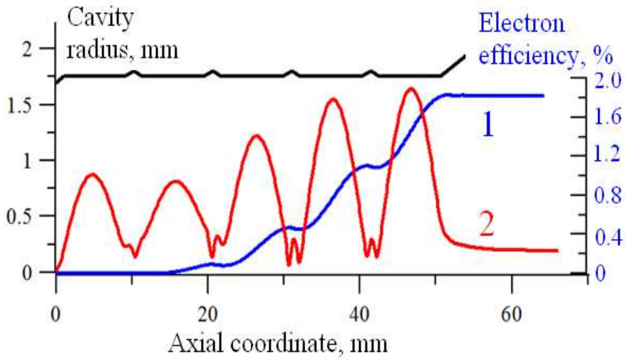

Figure 5. The quasi-regular cavity cavity designed for the fourth-cyclotron-harmonic operation, and results of numerical simulations (axial structure of the operating wave and the electron efficiency versus the axial coordinate).

6 Acknowledgements

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7 References

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