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Frequency Tunable sub-THz Gyrotrons for Spectroscopy Applications

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Development of methods of sub-THz medium-power (0.01 to 1 kW) radiation generation with wide-band (several per cent) frequency tuning provides new possibilities for relevant fundamental and engineering applications. In particular, direct measurement of positronium hyperfine structure [1] would allow an experimental verification of a number of quantum electrodynamics predictions. On the other hand, CW tunable coherent radiation with specified parameters can be used in spectroscopy for detection of very small-intensity molecular spectra using the method of radio-acoustic detection of absorption (RAD spectroscopy [2-4]). Most powerful and simultaneously most compact and accessible devices operating in the sub-THz range are the gyrotrons which have already confirmed their significance for a number of present-day issues. At the same time, one of gyrotron features is fairly narrow (less than percent) frequency tuning band which is a substantial limitation for gyrotron applications.

The main obstacle for implementation of a gyrotron with wide frequency tuning band is high Q-factor of the operating mode with one longitudinal variation near the cutoff frequency. Thus, for provision of smooth frequency tuning, excitation of higher longitudinal modes with relatively low Q-factor in the long resonators was usually used [5,6]. However, in this case, the part of Ohmic losses raise dramatically and, on the other hand, sensibility to the velocity spread in the electron beam increases. Both reasons lead to significant decrease in output power and strongly limit the frequency tuning.

In this paper, in contrast to most of the previous works, we propose using a relatively short cavity with low Q-factors to provide efficient excitation of a number of high-order axial modes. The main idea of the proposed method is exploiting the weaker sensitivity of a short-cavity gyrotron to the velocity spread in the electron beam. In fact, on a short resonator length the velocity spread does not have time for a significant influence on the electron-wave interaction process. At the same time, it is obvious that the shortening of the resonator will require increasing the current of the gyrotron electron beam. In addition to providing the starting conditions for exciting high-order longitudinal modes, it will also provide overlapping of the generation zones at neighboring modes. At the same time, the required current value can be substantially reduced by going to operation at low transverse modes due to the growth of the electron-wave coupling coefficient. These considerations make it possible to expect that, with a certain optimization, such approaches can provide a sufficiently wide band of gyrotron generation.

Further using the KARAT code [7] we carried out PIC simulations for two gyrotron schemes. The first gyrotron with a frequency of about 200 GHz, a power of 0.5-1 kW and a tuning band of about 5% is intended for direct spectroscopy of positronium. The second gyrotron with a frequency of about 164 GHz, a power of 0.1-0.3 kW and a tuning band of about 3% is planned to be used for RAD spectroscopy experiments. The main parameters for both schemes are shown in Table 1.

Table 1. Parameters of tunable sub-THz gyrotrons

Operating voltage	20 kV	15 kV
Beam current	1.5-2A	0.4A
Pitch-factor	1.0	
Operating mode	TE_{12}	TE_{02}
Cavity radius	1.25 mm	2 mm
Cavity length	12-16 mm	20 mm
Beam injection radius	0.72 mm	0.55 mm
Operating frequency	~204 GHz	164 GHz
Tuning band	~5%	~3%
Output power	0.5-1 kW	0.1-0.3 kW

Further results of PIC-simulations are presented in detail for the case of 200 GHz gyrotron. The geometry of interaction space and instantaneous positions of charged macroparticles are shown in Fig.1a,b. The simulations evidence that for the velocity spread of 20% the radiation power exceeds 0.5 kW in the entire frequency tuning band of 10 GHz (5%) (see curve 1 in Fig.2). For this region of the magnetic field, from 7.3 to 8.6 T, stationary single-mode excitation of the operating TE_{12} mode takes place (Fig. 1c). For a magnetic field higher than 8.6 T, the excitation of the parasitic transverse TE_{51} mode occurs, which limits the further increase in the bandwidth. The use of the proposed gyrotron operation regime with a short cavity and a high electron current ensure a wide frequency tuning band even for a very high spread, 50%. This result confirms the small influence of the velocity spread on the electron-wave interaction for short-cavity gyrotron.

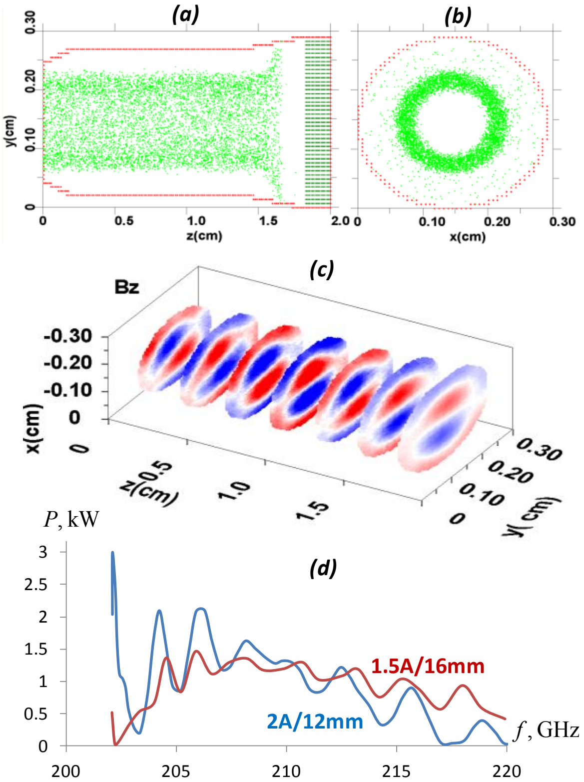

Fig.1. (a, b) Geometry of the gyrotron cavity used in 3D PIC simulations of 200 GHz gyrotron. (c) The transverse structure of the excited TE_{12} mode. (d) The gyrotron output power vs. radiation frequency for different cavity lengthes and electron currents

It should be noted that for the further improvement of the output characteristics of a tunable gyrotron, methods for reducing ohmic losses and eliminating gaps on the power vs frequency curve should be employed. These possible methods, which are the subjects of the further research, include a smooth taper at the output end of the cavity [6,8], a cavity profile taper [9], and a cathode-end power output configuration of the device [10,11].

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