Some Advantages of the Gyrotrons with Width Emitters

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Abstract: *The main trends in gyrotron development are escalation of the radiated power and increasing the frequency of coherent radiation. For both trends it is beneficial to develop gyrotrons with wide emitters because this allows one to use cryomagnets with smaller inner bore sizes. For analyzing and optimizing the operation of gyrotrons with wide emitters it is proposed to represent such emitters as a superposition of thin rings and analyze the properties of electron beams emitted by each of these rings. The analysis of electron beam properties, for electron optical systems with different emitters is presented. The possibility to reduce velocity spread by anode profiling is discussed. The dynamics of electron beam and interaction efficiency for different emitters are calculated.*

Keywords: gyrotron, magnetron-injection gun, electron beam, emitter, width, interaction efficiency

Introduction

There is a growing interest in developing high-power THz-range gyrotrons for various applications. Such gyrotrons operate in superconducting solenoids, whose cost rapidly increases with the diameter of the inner bore. This size of the inner bore limits transverse sizes of all elements of electron guns and, in particular, the diameter of emitters. Therefore to increase the gyrotron power (and/or decrease the cost of gyrotrons with a given power level) it makes sense to keep the diameter of emitters fixed, but to increase the emitter thickness. The thickening of annular beams, however, may lead to increases in the spread in electron guiding center and velocities; both of these cause efficiency degradation. Effects of the beam thickness on the gyrotron performance were studied in many papers; see, for example, Refs. [1, 2] for studies of efficiency degradation and Refs. [3-5] for studies of mode competition. This beam widening also may cause interception of the outermost electrons by the walls of the beam tunnel and resonator entrance, so the gyrotron design should, of course, be made providing sufficient clearance between the beam and the walls. These report present preliminary results of electron beam parameters and interaction efficiency calculation for gyrotrons with different width of emitter.

Modeling Of Electron Beam Parameters And Interaction Efficiency

As the first step, the optimization of the electron system was focused, as always, on the possibility to form an electron beam with a large pitch-ratio (orbital-to-axial velocity ratio) and small velocity spread. The modeling has been made for 28 GHz gyrotron, which gave a possibility increase the speed of calculation, due to relatively big wavelength and, correspondently, geometry scale and grid. The overview of EOS is presented in Fig.1.

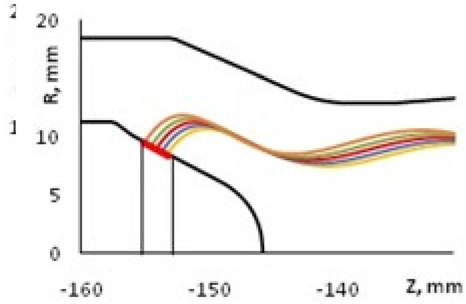

Fig. 1. Electron optical system of technological gyrotron.

In view of the fact that the present study is focused on wide emitters, it was also necessary to take into account the spread of electron guiding centers in the cavity. First, characteristics of an electron beam emitted by the standard emitter consisting of 5 layers have been studied. The properties of each emitter layer were studied by considering 20 000 electron trajectories. Then, a similar study was performed for a wide emitter consisting of 7 layers; correspondingly, the total beam current was increased by a factor 1.4. It was assumed that the electron beam voltage is in the range of 20-25 kV, the beam current in the case of the standard emitter is 2.4 A, the cathode loading is 2.1 A/cm^2 and electric field at the cathode surface is about 2.7 kV/mm.

In simulations the codes EPOS and ANGEL were used, which allow one to calculate the electron trajectories in the external electric and magnetic fields from the cathode to the cavity region and determine characteristics of the resulting electron beam. The codes are based on solving the two-dimensional (2D) cylindrical Poisson equation in predefined electrostatic and magnetic fields and include the space-charge fields. In addition to these codes, also the particle-in-cell code CST Studio Suite has been used. So, not only the properties of electron fractions emitted by the slices of the emitter were studied, but also 3D modeling of the entire beam was carried out, taking into account the space charge fields. Then, a complete set of parameters (rotational velocity spread, pitch-factor, radial coordinates of electron guiding centers) for each fraction of the beam was obtained.

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Some non-uniformity in the distribution in transverse velocities in the thin layers was recognized, however, in all cases these velocities vary in practically the same range: from 0.243 to 0.249 in the standard EOS and from 0.244 to 0.249 in the EOS with a wide emitter. These results are obtained in the systems with a simple geometry: the cathode and anode surfaces are parallel to each other. As is widely known, the non-uniformity in distribution in orbital velocities can be mitigated by various means; one of the simplest is the profiling of the anode surface. The efficiency of interaction of electron fractions with the resonator field was calculated by using the self-consistent, time-dependent and multimode formalism. The efficiency of electron fractions in the gyrotron with electron optical systems shown in Fig. 1 is presented in Fig. 2. These data show the efficiency of the gyrotron operating in the $TE_{-1,2}$-mode. As shown in Fig. 5, in a gyrotron with a widened emitter the left additional layer operates with the highest efficiency (about 44%), while the right additional layer exhibits the lowest efficiency (19%). The total efficiency of all layers in a gyrotron with a wide emitter is almost the same as in a prototype gyrotron: 33% versus 34%. Note that these efficiencies do not represent the results of complete optimization of gyrotron parameters, but just are used for illustrative purposes.

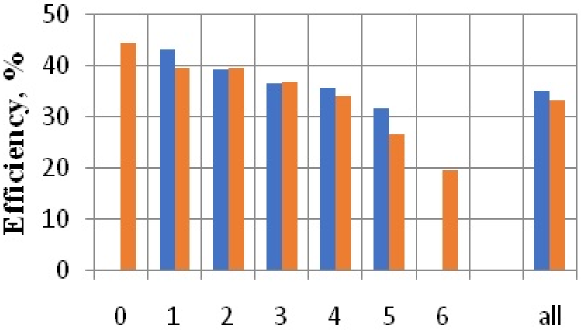

Fig.2. Efficiency of interaction for the gyrotron with standart and wide emitters

As mentioned above, for wide emitters, in efficiency calculations it is necessary to take into account the radial spread of electron guiding centers. Having a complete set of parameters for each fraction, the corresponding efficiencies were calculated by using a self-consistent system of equations. Results are presented in Fig. 3.

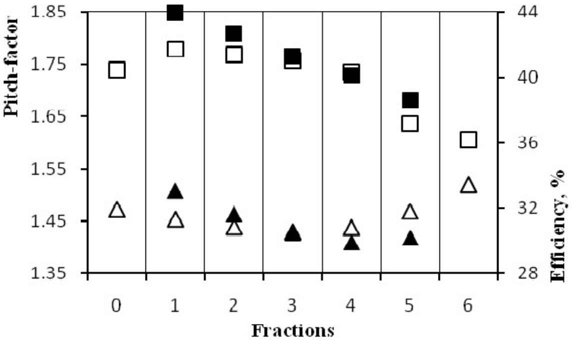

Fig.3. Efficiency (square) and pitch-factor (triangle) for different fractions for a gyrotron with a "standard" (black) and wide (empty) emitter.

From Fig. 3 it can be seen that it is not necessary to achieve close values of pitch factor (rotational speed) for each of the fractions of the beam. On the contrary, especially in the case of wide emitters, the far-right faction is noticeably inferior in terms of efficiency and requires large values of the pitch. At the same time, the increase in the efficiency of the extreme fraction is quite weak and has limitations. It is therefore proposed that optimization of the MIG with non-standard approach angles of the magnetic field lines relative to the start zone of the electrons in the emitter, would lead to less radial variation, and thus greater efficiency.

Summary

Results obtained illustrate some advantages of characterizing gyrotron operation by considering the characteristics of electron fractions produced by thin layers of wide emitters. Of course, the widening of emitters, while allowing the development of more compact gyrotrons, also causes some negative consequences. One of them is the increase of the beam radial thickness that causes the efficiency degradation due to the radial non-uniformity of the transverse structure of the resonator mode. Long ago it was assumed that for neglecting this negative effect the spread in radii of electron guiding centers in resonators should not exceed 1/8 of the wavelength. Later, this limited range of the radial spread was increased to 1/4 of the wavelength. In general, this beam thickness can be reduced by decreasing the angle between the magnetic force line and the emitter surface; optimization of the velocity distribution function in this case requires additional studies of the effect of the cathode and anode shapes on the velocity spread. It should be noted, however, that the above mentioned restriction on the beam thickness is valid for the case when we assume that the electrons with different radii of guiding centers have identical velocities. In principle, this problem for gyrotrons with wide emitters can be solved (or, at least, mitigated) by forming electron beams, in which electrons with guiding center radii corresponding to the maximum interaction with the resonator mode have lower orbital velocities than electrons whose guiding center radii correspond to weaker interaction with the mode.

It is shown that the widening (by less than a factor of two at least) may cause only a small decrease in the gyrotron efficiency. The proposed characterization of beam fractions can be important not only for optimizing the distribution of electron velocities, but also for maximizing the device efficiency. Such optimization can be greatly improved by combining the analytical methods with existing numerical codes.

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References

[1] O. Dumbrajs and G. S. Nusinovich, Phys. Plasmas, **19**, 103112 (2012)

[2] R.Pu, G.S.Nusinovich, O.V.Sinitsyn, and T.M. Antonsen, Jr., Phys. Plasmas, **17**, 083105 (2010)

[3] G. S.Nusinovich, Radiophys. Quantum Electron., **19**, 1301-06 (1976)

[4] N.S. Ginzburg, M.Yu. Glyavin, A.M. Malkin, V.N. Manuilov, R.M. Rosental, A.S. Sedov, A.S. Sergeev, V.Yu. Zaslavsky, I.V. Zotova, and T.Idehara, IEEE Trans. Plasma Sci., **44**, 1303-09 (2016)

[5] T. Idehara, M. Glyavin, A. Kuleshov, S. Sabchevski, V. Manuilov, V.Zaslavsky, I. Zotova, and A. Sedov, Rev. Sci. Instrum., **88**, 094708 (2017)