New possibilities of collectors with azimuthal magnetic field for multistage energy recovery in gyrotrons

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Abstract. The results of modeling a collector with 4-stage recovery of residual electron energy for the SPbPU gyrotron with a frequency of 74.2 GHz and an output power of 100 kW are presented. For spatial separation of electrons with different energies, an azimuthal magnetic field created by a toroidal solenoid is used. An increase of the recovery efficiency and a decrease of the current of electrons reflected from the collector is achieved by reducing the spread of the radial position of the leading centers of electron trajectories at optimal parameters of the toroidal solenoid, as well as by using a sectioned electron beam. The trajectory analysis of the spent electron beam in the collector region showed the possibility of achieving the total efficiency of the gyrotron, close to 80%.

1. Introduction
An important challenge facing developers of high-power gyrotrons for energy applications is the increase of their total efficiency. This problem can be solved by using collectors with recovery of residual energy of the helical electron beam (HEB). In the single-stage recovery scheme, typical total efficiency values for high-power gyrotrons are 50-55% [1,2,3]. The efficiency of energy recovery is increased by transition to multistage depressed collectors, in which spatial separation of beam fractions with different electron energies and deposition of these fractions on collector sections under different potentials are realized. It is shown that a promising method for spatial separation of electrons in HEB is using the crossed electric and azimuthal magnetic fields [4,5,6]. Recently, SPbPU has developed collectors with multistage energy recovery, that are based on a new method of electron separation in the azimuthal magnetic field formed by a toroidal solenoid [5,7,8,9].

This paper presents the results of simulation of the 4-stage depressed collector for the experimental SPbPU gyrotron with an operating frequency of 74.2 GHz and an output power of 100 kW (e.g. [10,11,12]). New solutions were implemented for optimization of toroidal solenoid parameters, which made it possible to increase the efficiency of residual HEB energy recovery. Calculations were carried out using the CST Studio Suite 3D modeling software [13].

2. Design of a multistage depressed collector for the SPbPU gyrotron
There is a relatively strong magnetic field in the collector region of gyrotrons, which makes it difficult to implement multistage recovery systems similar to systems applied in other vacuum microwave devices such as klystrons, travelling wave and backward wave tubes, etc. In gyrotrons, a new method based on the use of crossed longitudinal electric and azimuthal magnetic fields can provide spatial
separation of electrons with different energies and deposition of these electrons on the collector sections under different potentials [5].

Figure 1 shows the model of the collector for the SPbPU gyrotron. The energy recovery is carried out in the cylindrical part of the collector body, where the electrode-sections I—IV under the retarding potentials are located. In this region, correction collector coils in combination with the main magnetic system of the gyrotron (not shown in the figure) create a quasi-uniform longitudinal magnetic field $B_z$. A toroidal solenoid is used to form the azimuthal magnetic field concentrated in the area restricted by external and internal windings and also by end face conductors of the solenoid. End face conductors located on the side closest to the cavity prevent passing of electrons into the recovery region. In the described design, these conductors are assembled into two radial bundles, which increases the portion of electrons passed into the recovery region. However, the amplitude of the parasitic magnetic field in the area near the bundles increases, which negatively affects the electron trajectories in this area. This parasitic field causes a spread of radial position of the leading centers of electronic trajectories in the recovery region. This spread leads to a decrease of recovery efficiency, since a part of electrons after changing the direction of the longitudinal velocity may not deposit to collector section corresponding to their energy and deposit on sections under a more positive potential. There is also a possibility for these electrons to leave the collector region and to enter the cavity.

In order to reduce the number of electrons whose trajectories are noticeably distorted near the bundles, a sectioning of the HEB can be performed. For this purpose, a sectioned cathode in which electron emission from two (determined by the number of bundles of the toroidal solenoid) azimuthal sectors of the emissive strip is absent [8].

![Figure 1. Schematic drawing of the gyrotron collector.](image)

3. Results of the trajectory analysis in the gyrotron collector region

The first calculations were performed with the positive direction of the azimuthal magnetic field $B_{\theta^+}$ (see Figure 1). In this case, electron drift in the crossed $E_z \times B_{\theta^+}$ fields is directed towards larger radii. The cone shape of sections I—IV provides the slight varying of the amplitude of the longitudinal electric field $E_z$ along the $z$ axis in the recovery region. For trajectory analysis in the collector region, an input interface with the data on approximately $25 \cdot 10^3$ particles obtained after PIC simulation of electron beam interaction with electromagnetic field in the cavity was used [8]. This simulation was performed for the operating regime of the gyrotron with accelerating voltage $U = 30$ kV and beam current $I_b = 10$ A, in which high quality of the HEB and increased electronic efficiency ($\eta_e = 46\%$) were achieved due to optimization of distributions of electrical and magnetic fields in the electron-
optical system. A sectioned cathode with no electron emission from two sectors of length 70° was used for the HEB formation.

The following voltages on the collector sections were selected: \( U_1 = -7.72 \text{ kV} \), \( U_2 = -10.72 \text{ kV} \), \( U_3 = -14.72 \text{ kV} \), \( U_4 = -24.72 \text{ kV} \) (collector body was connected to the gyrotron body). At these voltage values, the total gyrotron efficiency has its maximum in the condition of an ideal separation, when each energy fraction of the beam is deposited on a section whose voltage corresponds to the energy of this faction [8]. In the recovery region where the sections were located (see Figure 1), induction of the longitudinal and azimuthal components of the magnetic field were equal to 0.04 T and 0.08 T, respectively. In this regime, the trajectory analysis was resulted in the following values of the power dissipated on the sections and on the collector body: \( P_1 = 36.15 \text{ kW} \), \( P_2 = 4.79 \text{ kW} \), \( P_3 = 5.24 \text{ kW} \), \( P_4 = 7.58 \text{ kW} \), \( P_{\text{coll}} = 0.43 \text{ kW} \). The total power dissipated on the collector \( P_{\text{diss}} \) was 54.19 kW, and the total efficiency of the gyrotron \( \eta \) was 71.8%. The current of electrons reflected from the collector towards the resonator was 1.37% of the total beam current. The first calculations showed prospects for using the azimuthal magnetic field for separation of electrons with different energies in the spent HEB of gyrotrons. However, there are still opportunities to improve the recovery efficiency. The reason for lack of efficiency is associated with the action of the parasitic magnetic field of the bundles at the end face of the toroidal solenoid. In the simulation of the collector for the DEMO prototype gyrotron [9], new solutions were found to reduce the influence of this magnetic field.

These solutions were used for modernization of the collector for the SPbPU gyrotron. One of the solutions was to change the direction of the azimuthal magnetic field from positive \( B_{\theta} \) to negative \( B_{\theta} \). As a result, the direction of the Lorentz force acting on electrons entering into the region with the azimuthal magnetic field is also changed. This force will shift electrons towards greater radii at a negative field \( B_{\theta} \). Radial shift of electrons also occurs as a result of the action of the force associated with the change in the longitudinal magnetic field along the \( z \) coordinate. In the case of the negative field \( B_{\theta} \), one of these forces partially compensates for the other, which results in a decrease of the

![Figure 2. Trajectories of "single" electrons with different azimuthal coordinate \( \theta \) of the particle point source calculated in the \( r-z \) plane at positive (a) and negative (b) directions of azimuthal magnetic field.](image-url)
spread of the radial position of electron trajectories. An additional reduction of this spread can be achieved by choosing the optimal values of the length of the cone part of the toroidal solenoid and the angle of inclination of this cone part to z axis (see Figure 1).

Figure 2 shows the projections of the trajectories of "single" electrons on the r–z plane for a positive $B_\theta$, (Figure 2 (a)) and negative $B_\theta$, (Figure 2 (b)) directions of the azimuthal field. In these calculations, point sources of electrons with an energy of 20 keV and with different azimuthal positions $\theta$ of the emission point were set in the input plane of the collector $z = 320$ mm ($z = 260.5$ mm – the central plane of the cavity). The positions of the bundles of the toroidal solenoid correspond to azimuthal angles $\theta = 90^\circ$ and $\theta = 270^\circ$. It can be seen that change of azimuthal field direction from positive to negative noticeably decreases the spread of the radial position of the electron trajectories in the recovery region ($z > 600$ mm). Trajectories shown in Figure 2 were obtained for the length of cone part of the toroidal solenoid equal to 40 mm and for the angle of cone part inclination equal to $10^\circ$.

The change of the direction of the azimuthal field made it possible to reduce the parasitic influence of the bundles. However, the distortion of trajectories still remains for electrons that move in close vicinity of the bundles (see $\theta = 45^\circ$ and $\theta = 67.5^\circ$ in Figure 2 (b)). In order to exclude the influence of such electrons, it is necessary to use a sectioned HEB formed with an electron gun with a sectioned cathode (see above). Obviously, the sectioning of the beam can decrease its quality and reduce the efficiency of beam interaction with the high-frequency field in the cavity. Figure 3 (a) shows the dependences of the average pitch factor $\alpha$, which is equal to the ratio of transverse to longitudinal electron velocity, and the transverse velocity spread $\delta v_{tr}$ on azimuthal length $\theta_{sect}$ of the cathode sectors without electron emission. These dependences were obtained as a result of trajectory analysis in the electron-optical system of the SPbPU gyrotron. When the angle $\theta_{sect}$ was varied, beam current $I_b$ maintained equal to 10 A. The values of $\alpha$ and $\delta v_{tr}$ characterize the quality of the beam entering the cavity. This beam was then used as an input interface for PIC simulation of the interaction of electrons with the electromagnetic field in the cavity. As a result of this simulation, the dependence

![Figure 3](image_url)
shown in Figure 3 (b) was determined and a set of data on the parameters of the spent HEB at different \( \theta_{\text{sect}} \) were obtained in order to perform trajectory analysis in the gyrotron collector region. As it is shown in Figure 3, the sectioning of the HEB leads only to a slight decrease of the beam quality and of the gyrotron electronic efficiency, which can be compensated by the increase of total efficiency provided by spent beam energy recovery in the collector region.

The trajectory analysis in the collector region was performed with the optimized parameters of the toroidal solenoid: negative direction of the azimuthal magnetic field \( B_\phi \), the length of the cone part of the solenoid equal to 40 mm, and the angle of cone part inclination equal to \( 10^\circ \). With optimal values of the parameters: \( U_\text{I} = -8.0 \text{ kV} \), \( U_\text{II} = -11.2 \text{ kV} \), \( U_\text{III} = -21.7 \text{ kV} \), \( U_\text{IV} = -28.2 \text{ kV} \), \( B_\phi = 0.06 \text{ T} \), \( \theta_{\text{sect}} = 45^\circ \), the total efficiency of the gyrotron equal to about 80% was obtained with a current of electrons reflected from the collector less than 2% of the total HEB current.

4. Conclusion

Thus, the modeling of the collector for the SPbPU gyrotron carried out in this work confirmed the possibilities of effective separation of electrons of the spent HEB, based on their drift in the crossed azimuthal magnetic and axial electric fields. Optimization of the parameters of the toroidal solenoid, which is used to create an azimuthal magnetic field, made it possible to increase the total efficiency of the gyrotron with a 4-stage depressed collector up to about 80%.

References

[1] Sakamoto K, Tsuneoka M, Kasugai A, Imai T, Hayashi K, Mitsunaka Y 1994 Phys. Rev. Lett. 73 (26) p 3532
[2] Glyavin M Y, Kuftin A N, Venediktov N P, Zapevalov V E 1997 Int. J. Infrared Millim. Waves 18 p 2129
[3] Thumm M 2020 Int. J. Infrared Millim. Waves, 41 (1) pp 1-140
[4] Pagonakis I Gr, Hogge J-P, Alberti S, Avramides K A, Vomvoridis J L 2008 IEEE Trans. Plasma Sci. 36 (2) p 469
[5] Louksha O I, Trofimov P A 2015 Tech. Phys. Lett. 41 (9) p 884
[6] Wu C, Pagonakis I G, Avramidis K A, Gantenbein G, Illy St, Thumm M, Jelonnek J 2018 Phys. Plasmas 25 (3) 033108
[7] Louksha O I, Trofimov P A 2017 Proc. 18th Int. Vacuum Electronics Conf. (London) (NY: IEEE) p 1
[8] Louksha O I, Trofimov P A 2019 Tech. Phys. 64 (12) p 1889
[9] Louksha O I, Trofimov P A, Manuilov V N, Glyavin M Yu 2020 Int. Conf. Infrared Millim. Waves (Buffalo), (NY: IEEE) p 883–884
[10] Louksha O I, Piosczyk B, Sominski G G, Thumm M K, Samsonov D B 2006 IEEE Trans. Plasma Sci. 34 (3) pp 502–511
[11] Louksha O I, Sominski G G, Arkhipov A V, Dvoretskaya N V, Kolmakova N G, Samsonov D B, Trofimov P A 2016 IEEE Trans. Plasma Sci. 44 (8) pp 1310–1319
[12] Louksha O I 2009 Radiophys. Quantum Electron. 52 (5-6) pp 386–397
[13] https://www.3ds.com/products-services/simulia/products/cststudio-suite/