Development of multistage energy recovery system for gyrotrons

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Abstract. A four-stage depressed collector based on spatial separation of electrons with different energies in the crossed electric and magnetic fields was developed for the experimental SPbPU gyrotron. Modeling of the system of electron energy recovery and analysis of the distributions of electric and magnetic fields in the gyrotron collector region were performed. As a result of the theoretical estimations and the trajectory analysis of the helical electron beam, it is shown that the developed system provides recovery of the residual electron energy necessary to achieve the total efficiency of the gyrotron exceeding 70 %.

1 Introduction

Modern gyrotrons are microwave sources generating high output power in millimeter and submillimeter wavelength ranges, which substantially exceeds capability of conventional vacuum microwave devices such as traveling-wave tubes, magnetrons, klystrons, etc. [1]. Gyrotrons have already become highly required tools for electron current drive and plasma heating in controlled fusion experiments. Gyrotrons are also used for particle acceleration, in high-resolution spectroscopy, for material processing and for other applications [1, 2].

The gyrotron is a cyclotron resonance maser that uses the energy of helical electron beam (HEB) concentrated in transverse motion of electrons to generate high-frequency electromagnetic radiation. The electron efficiency of gyrotrons determined by the electron energy transferred to high-frequency radiation does not usually exceed 30–35 % [2]. The total efficiency can be increased by a system of energy recovery placed in the collector region in which electrons of the spent beam are decelerated. Deceleration of electrons allows to decrease beam power deposited in the collector, in other words, to return a part of the beam power back to the electric circuit and to diminish the collector thermal loading.

Presently, high power gyrotrons are usually equipped with one-stage energy recovery systems that allow increasing the total efficiency up to 50–55 % [1-3]. The further increase of total efficiency is possible with implementation of multistage systems of energy recovery. Such systems have to separate the electron beam on fractions with different energy of electrons and provide deposition of these fractions on sections under different potentials [4-9]. The magnetic induction in the collector region of gyrotrons is noticeably less than in the resonator. As a result, major part of electron energy is concentrated in the

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longitudinal (along magnetic field lines) motion, which can simplify implementation of multistage energy recovery. Increase of the number of deceleration stages leads to enhancement of the total efficiency. However, as we know, systems with multistage energy recovery have not yet been implemented in gyrotrons, possibly due to the inherent velocity and position spreads of electrons in the HEB, as well as due to the presence of a residual magnetic field in the collector region.

In order to achieve recovery of electron energy in a multistage depressed collector, a method of separation of electrons with different energy should be realized. A new approach to separation of electrons, based on their radial drift in the crossed electric and magnetic fields, was studied by several research groups (for example, [5-9]). The authors of this paper proposed to use the axial electric field and the azimuthal magnetic field with the aim of providing effective separation of electrons.

In this paper, the design of a 4-stage energy recovery system for the pulsed 74.2 GHz, 100 kW gyrotron [10] is discussed. The main criteria for selecting parameters of the collector electrodes and coils to achieve effective recovery of residual electron energy of the spent beam are determined. The analysis of field distributions in the developed recovery system allows to define limitations in the capabilities of this system and to suggest possible ways to reduce these limitations. In conclusion, the results of electron trajectory analysis of the spent beam are presented. These results show the possibility to achieve record values of total efficiency of the gyrotron.

2 Method of electron separation

The separation of electrons in the designed multistage recovery system results from introduction of the azimuthal component of magnetic field B_θ in addition to the axial magnetic component B_z confining the beam and the retarding axial electric field E_z. The mechanism of separation is based on the radial drift of electrons in the crossed axial electric and azimuthal magnetic fields.

Fig. 1 shows schematically the principle of the spatial separation. The trajectories of electrons with different initial energy W_i are presented. Electrodes (sections) under different potentials create the electric field, and magnetic field is produced by coils hidden in the scheme. The distribution of electric field along the direction of electron motion can be adjusted by changing the tilt angle of the sections. The velocity of radial drift $v_{dr} = E_z/B_\theta$ depends only on magnetic and electric field amplitudes and does not depend on energy of particles. Therefore, the distance of radial drift will be determined by the transit time of electrons moving in the region of crossed fields, which is defined by the initial energy W_i (Fig. 1). With proper selection of the electric and magnetic field amplitude, we can provide spatial separation of electrons with different energy resulting in deposition of beam

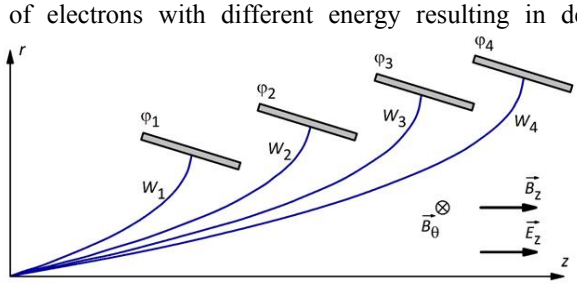

Fig. 1. Schematic drawing of electron separation in the crossed axial electric and azimuthal magnetic fields (initial electron velocity $\mathbf{v_0} \parallel \mathbf{B}$).

energy fractions on the sections under different potentials φ_i. The azimuthal and axial drifts caused by the combinations of fields $E_r \times B_z$ and $E_r \times B_\theta$ also exist but do not essentially affect the separation of electrons in this configuration of electrodes.

During motion of an electron in retarding electric field E_z, it can change the direction of its axial velocity to opposite direction. In the presence of a confining magnetic field B_z, such reflected electrons move adiabatically and can exit the collector region and reach the resonator if there is no enough radial drift to intercept them by one of the collector sections. In the resonator, these electrons can interact with high-frequency field and take energy from it decreasing output power of the gyrotron. Therefore, reflection of electrons should be reduced to the limit value of at least 1-2 % that can be acceptable for gyrotrons [11].

Meaning basic principle of the separation, it is possible to determine the requirements for the sources of electric and magnetic fields, which allow to realize an effective multistage energy recovery of the spent beam. First, the distance of radial drift of electrons during the movement in retarding field until they are deposited on one of the electrodes should significantly exceed the thickness of the hollow HEB. In this case, deposition of electrons occur without reflection to the resonator. Secondly, the amplitude of the electric and magnetic fields should vary slightly along the axial coordinate z in the region of electron deceleration. It is important for providing an acceptable length of the collector system at approximately equal thermal loading on each collector section. Thirdly, the magnetic and electric fields should change adiabatically in the transition region between the resonator and the collector. In the opposite case, electrons can acquire an additional transverse velocity, which increases probability of their reflection in the direction of the resonator.

3 The development of a 4-stage collector system for the SPbPU gyrotron

The modeling of the collector system was performed for a pulsed gyrotron of average power of ~ 100 kW. The main parameters of the gyrotron are shown in Table 1. Previously, this gyrotron was used for complex experimental study aimed at finding methods to enhance the quality of the HEB and, as a result, the efficiency of the device [10, 12, 13]. In this gyrotron, a triode-type magnetron injection gun (MIG) forms the electron beam. The magnetic system consists of solenoids which are powered by a capacitive storage bank operating in a single pulse regime.

Elements of the collector system were designed to provide multi-stage recovery of residual beam energy based on the requirements given in the Section 2. The three-dimensional drawing of the gyrotron collector model is shown in Fig. 2. Modeling of the collector system and calculation of electron trajectories were performed using the simulation code CST Studio Suite.

In the collector region, a series of Helmholtz coils is used for confinement of the spent electron beam. In combination with the coils of the main magnetic system of the gyrotron, these coils create a quasi-homogeneous distribution of the magnetic field B_z along the axial coordinate in the region of deceleration of electrons. The azimuthal magnetic field B_θ is generated by a solenoid with toroidal winding. Wires of the toroidal solenoid are grouped together and form two "wisps" before the entrance of the collector to provide access of electrons to the region of energy recovery (Fig. 2). Outer winding of the toroidal coil can be made using wires with an increased cross sectional area to improve the uniformity of the azimuthal field distribution along the azimuthal coordinate.

Four conical sections I-IV are used for creation of electric field in the energy recovery region. The electric potentials of sections decrease in direction from the resonator. The geometric parameters of the sections were chosen based on requirements of the section 2

Table 1. Parameters of the SPbPU gyrotron.

Parameter	Value
Accelerating voltage	U_0 = 30 kV
Beam current	I_b = 10 A
Resonator magnetic field	B_0 = 2.75 T
Operating mode	$TE_{12,3}$
Operating frequency	f_0 = 74.2 GHz
Duration of current pulse	τ = 30–60 μs

and on estimations of drift radial distance of electrons with different energies at given values of E_z and B_θ. Optimization of the section geometry was carried out according to the results of the trajectory analysis [14]. Conical form of the sections provides the deposition of the major part of particles on the their outer walls [14]. By changing the angle of electrode inclination, reduction of the incident angle is provided for primary electrons, which further reduces the thermal loading of the collector. Secondary electrons emitted from the collector can have a negative effect on the operation of the device, if there is a possibility of their moving toward the resonator. However, due to the presence of the crossed $E_z \times B_\theta$ fields and the conical shape of sections, such a possibility is practically excluded, which is one of the advantages of the considered spatial separation method [8].

Fig. 3 shows the distribution of the magnetic field components in the collector region. The image of the collector model in the cross-section of the "wisps" is shown in Fig. 3, *b*. Current in the "wisp" wires creates an additional axial magnetic field B'_z in its vicinity. This field has both the positive ($B'_z > 0$) and the negative ($B'_z < 0$) direction with respect to the direction of the field B_z created by the magnetic system of the gyrotron and by Helmholtz coils. Fig. 3, *a* shows the axial and azimuthal components of the total magnetic field as functions of the axial coordinate. The values of B_z, B'_z, B_θ for each *z* were determined at the

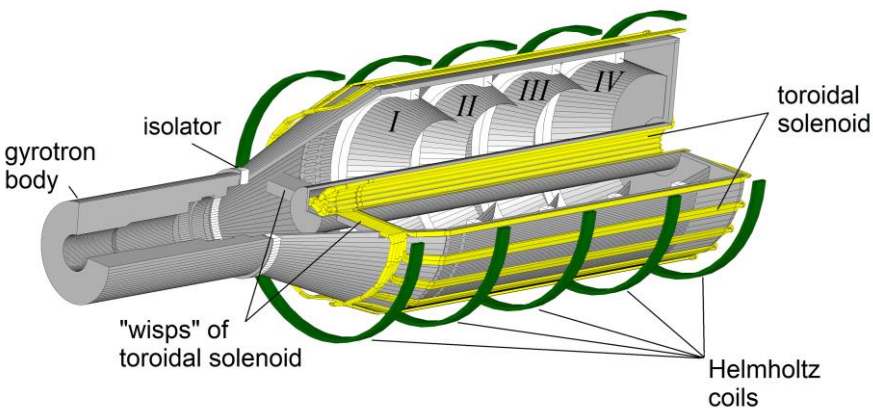

Fig. 2. Schematic drawing of the collector model.

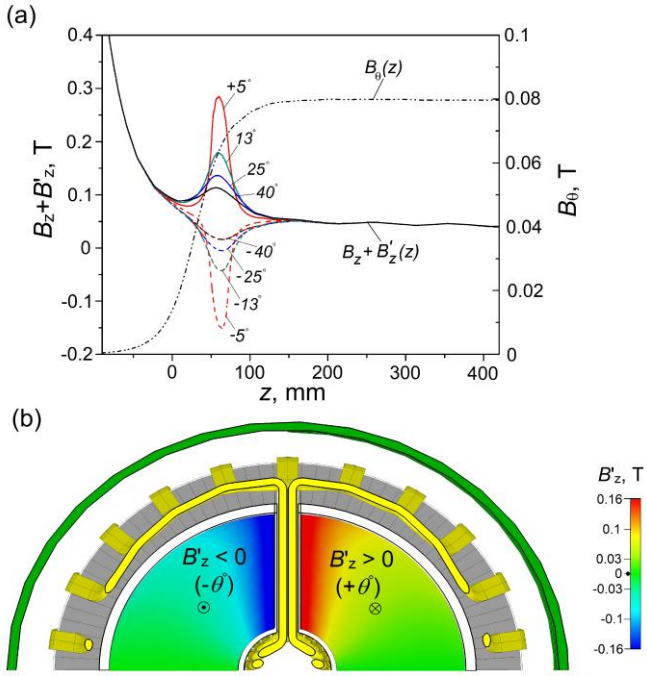

Fig. 3. (a) Distribution of magnetic field components in the collector along a typical electron trajectory at different azimuthal angle from the "wisp". Local inhomogeneity of the axial magnetic field $B_z+B'_z$ on the "increasing" side (+θ – solid lines) and the "decreasing" side (-θ – dashed lines) are presented. (b) Distribution of the axial magnetic field B'_z in the cross-section of the solenoid "wisp".

radial coordinate r corresponding to the average radius of the HEB calculated in the absence of magnetic field of the toroidal coil. Electrons that enter the separation area in the region of "+θ" angles (Fig. 3, *a*), can move at too small radii, and their drift distance can not be enough to deposit on one of the sections. Such electrons increase the coefficient of reflection from the collector. If electrons enter the collector in the region of "–θ" angles, the total axial magnetic field along their trajectory can change the direction to opposite. Such a reversal of magnetic field leads to a noticeable change in electron transverse velocity and also to an increase of reflection of electrons.

To reduce the disturbing effect of the magnetic field of the "wisps", a sectioned electron beam was used in the calculations. This beam was formed by a sectioned cathode included two sectors with no emission, the azimuthal positions of which corresponded to the azimuthal location of the "wisps" [14]. Based on the results of the trajectory analysis, optimal length of these sectors in the azimuthal direction was chosen to be 70°. With the help of the sectioned electron beam, the percentage of electrons reflected from the collector was significantly reduced compared with the uniform beam. In the separation region ($z > 150$ mm), the longitudinal component of magnetic field induction B_z varies slightly along the z coordinate and is equal to approximately 0.05 T.

The trajectory analysis [8] showed that the average radius of the beam $R_{av} \approx 55$ mm and the beam thickness $\Delta R \approx 3$ mm at $B_z = 0.05$ T. In the recovery region, the value B_θ is equal to approximately 0.08 T (Fig. 3, *a*). Analytic estimations obtained from solving the equations of motion of electrons in these fields show that the drift distance at typical values of electron initial energy is significantly higher than ΔR. For example, if $B_z = 0.05$ T, $B_\theta = 0.08$ T and $E_z = 1$ kV/cm, the trajectory of an electron up to time of its reflection shifts

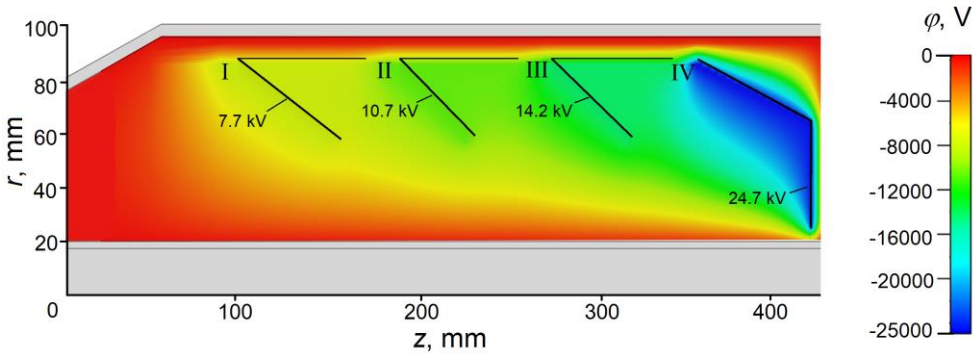

Fig. 4. Gradient image of electric potential distribution in the cross-section of recovery system.

radially on the distance ΔR_{dr} from 7 to 14 mm when changing the initial energy from 8 to 38 keV. Note that, since the main part of electrons is deposited on the outer walls of the collector sections, the radial drift distance exceeds ΔR_{dr}.

In order to determine the characteristics of the spent beam, calculations of electron trajectories in the electron optical system of the gyrotron and then calculations of the interaction of HEB with high-frequency field in the resonator were carried out [14]. A sectioned HEB was used in these calculations. A control electrode was included in the MIG, which gave the possibility to regulate the distribution of electric field in cathode region [14, 15]. The following calculations were performed for the regime of the gyrotron characterized by the high quality HEB with the low velocity spread $\delta v_{\perp}$ = 3.4 % and with the average pitch ratio $\bar{\alpha} = v_{\perp}/v_{\parallel} = 1.52$. In this regime, the calculated values of the output microwave power P_{RF} and electronic efficiency of the gyrotron η_{el} were 138 kW and 46 % respectively. The data of the spent HEB in the output port of the resonator consisting of about $25 \cdot 10^3$ particles [14] were served as input data for the calculation of the electron trajectories in the collector.

As a result of the optimization, the following values of potentials of the collector sections were selected: φ_I = -7.72 kV, φ_{II} = -10.72 kV, φ_{III} = -14.72 kV, φ_{IV} = -24.72 kV. These potentials are specified in relation to the grounded collector body. The distribution of the potential in the collector region at these potentials of the sections is shown in Fig. 4. To provide a quasi-uniform longitudinal electric field in the recovery region (z > 150 mm), the collector sections were equipped with the cylindrical elements which shielded the working space from the grounded collector.

The trajectory analysis of the collector with optimized geometry of sections and mentioned values of potentials $\varphi_{I\text{-}IV}$ allowed to obtain the value of the power dissipated on the collector P_{diss} equal to 54.19 kW at the current of reflected electrons equal to 1.37 % of the total beam current I_b = 10 A. In the considered regime of the gyrotron, the total efficiency of the device was achieved to be 71.8 % at the recovery efficiency of 66.5%.

4 Conclusion

The design of a 4-stage energy recovery system based on the method of spatial separation of electrons in the crossed azimuthal magnetic and axial electric fields was developed. The numerical simulation showed that the practical implementation of multistage collectors is possible for pulsed gyrotrons such as the experimental SPbPU gyrotron.

Trajectory analysis shows the possibility of achieving the necessary spatial separation of electrons with different energies in the presence of initial radial coordinate spread and

electron velocity spread. Drawbacks of the proposed collector system are mainly related to the local inhomogeneity of the magnetic field created by the "wisps" of the toroidal solenoid. A possible solution to reduce the negative effect of this inhomogeneity on recovery efficiency can be the use of a sectioned cathode. In the optimized regime of the gyrotron, the total efficiency of 71.8% was achieved with the recovery efficiency of 66.5% and the reflection coefficient of 1.37% of the total current of the beam.

Using the simulation data, a 4-stage collector system for the SPbPU gyrotron was designed and manufactured. The first experimental results showed the possibility of achieving the total efficiency of 60 % in a single-stage regime, which allows us to hope for the successful implementation of a multi-stage recovery scheme. The possibilities of further improvement of the developed method of recovery are connected with the improvement of the design of magnetic system providing the required distribution of the azimuthal magnetic field.

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