Development of the gyrotron collector system with multistage energy recovery

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Abstract. A collector system with 4-stage energy recovery for the 4-mm experimental gyrotron of SPbPU was developed. The utilized principles of spatial separation of the beam are described, as well as the main features of suggested collector system design. Feasibility study of the developed multistage energy recovery system was performed on the basis of electron beam trajectory analysis and simulation of electric and magnetic field distributions. This study proved that the suggested scheme is efficient and that the designed system is capable of successful operation. The possible problems associated with local magnetic field fluctuations and the method of their solution are discussed.

1. Introduction
Gyrotrons are presently acknowledged as the absolute leaders among the electromagnetic radiation sources for millimeter and submillimeter wavelength bands. In the wavelength gap, where the traditional vacuum and the optical devices both fail to exhibit acceptable performance parameters, gyrotrons provide high efficiency and output power thus finding applications in various fields such as cyclotron on plasma heating in tokamaks and stellarators [1, 2], high-resolution spectroscopy, material treatment and some other applications [3-5].

Gyrotron is a cyclotron resonance maser (CRM) using the energy of its helical electron beam (HEB) to generate electromagnetic radiation. Electrons emitted by the cathode of a magnetron injection gun (MIG) drift in the crossed (electric and magnetic) fields and acquire their initial velocity comprising of longitudinal and transverse components. Next, electrons enter the region where the magnetic field adiabatically increases, which leads to partial transfer of the longitudinal electron energy component into the transverse one. Then the electrons pass through the open cavity, where their transverse energy converts into the energy of electromagnetic oscillations due to the CRM instability.

The efficiency of electron energy conversion into radiation (electron efficiency) does not usually exceed 30-40 % [6]. The rest of the electron beam energy dissipates into the heat at the beam collector. The promising method for enhancing the total efficiency of gyrotron devices consists in the implementation of the energy recovery scheme known as the depressed collector. In the scheme, the electric field is used for deceleration of the spent electron beam. This results in a decrease of the collector thermal load and, most importantly, allows a part of the residual electron energy to be returned into electric circuit, which enhances the total efficiency of the device. Nowadays, single-stage depressed-collector systems are widely implemented in high-power gyrotrons. Total efficiency of such gyrotrons with one-stage depressed collectors is usually close to 50 % [7-9].
Further efficiency enhancement can be achieved with multistage depressed collector systems. In these systems, fractions of the beam with different electron energies are separated by using certain physical principles to be directed onto different sections of the collector [10, 11]. The most promising approach for separation of electrons consists in the introduction of crossed electric and magnetic field. Two main schemes are most commonly used. In one of them, azimuthal E-field component is introduced with the aid of a non-trivial collector design [12, 13]. The other way involves the creation of azimuthal magnetic field in the collector region. This method of separation of electrons has been previously suggested and studied by the authors of this paper [14, 15].

Here, we discuss the realization of a 4-stage depressed collector system with azimuthal magnetic field for the 74.2 GHz, 100 kW experimental gyrotron of the SPbPU [16]. We start with the general concept of electron beam separation by the crossed axial electric and azimuthal magnetic fields. Then, the developed design of 4-stage depressed collector system is presented. Distributions of electric and magnetic fields in this collector system were calculated and analyzed to determine the possible drawbacks and weak points of the present design. Finally, the methods for diminishing the found negative effects will be discussed.

2. Development of the gyrotron collector system

2.1. The basic concept

As it was mentioned above, the electric field is used for deceleration of the spent electron beam. In one-stage depressed collector scheme, the collector is placed under a negative potential, which leads to deceleration of electrons between the collector and device body. Although the spent beam in the collector region is still magnetized by a residual magnetic field from the gyrotron coils, the axial B-field in the collector is significantly (by the factor of ca. 100) weaker than one in the cavity. Consequently, electron velocities and energies are mostly longitudinal. In the one-stage energy recuperation scheme, a part of electron longitudinal energy returned to the feed circuit is:

\[ E_{rec} = \left| eU_{el} - e\varphi \right|, \]  

where \( eU_{el} \) is the residual electron energy and \( \varphi \) is the retarding potential of the collector (in case of the gyrotron body is grounded).

In the suggested multistage depressed collector system [14, 15, 17], in addition to the decelerating electric field, an azimuthal magnetic field is introduced. Radial drift velocity in the crossed axial E-field and azimuthal B-field may be determined from:

\[ v_{dr} = \frac{E_Z}{B_\theta}. \]  

As seen from (2), the drift velocity depends only on the field magnitudes and does not depend on the energy of electrons. The total drift distance is determined by the time that the electron remains in the crossed fields. Hence, this field configuration performs separation of electrons with different energies.

A multistage collector realizing this approach should consist of several insulated electrodes to allow application of a few different retarding potentials. If the needed spatial separation of the electron beam is achieved, different fractions of the spent beam can be directed onto different collector sections, allowing to return the most part of the residual electron energy back to electric circuit.

For realization of this principle, electric and magnetic field distributions should satisfy certain criteria:
1. Distributions of electric and magnetic fields in the region of energy recovery should be close to homogeneous.
2. Axial and azimuthal magnetic fields should change slowly (adiabatically) in the region between the cavity and the collector to prevent back-reflection of electrons into gyrotron cavity.

2.2. Design of the 4-stage collector system
In the framework of this study, a 4-stage depressed collector system was designed for the experimental gyrotron of the SPbPU [16, 18]. Its simulations were carried out in 3-D simulation software CST Particle Studio [19]. In this gyrotron, the magnetic system consists of several solenoids and operates in the single-pulse mode. The parameters of the operation regime of this gyrotron are presented in Table 1.

Table 1. Main parameters of the experimental SPbPU gyrotron.

| Parameter                  | Value    |
|----------------------------|----------|
| Accelerating voltage, $U_{acc}$ | 30 kV    |
| Beam current, $I_b$         | 10 A     |
| Frequency, $f_0$            | 74.2 GHz |
| Beam pulse duration, $\tau$ | 30–60 $\mu$s |
| Magnetic field in the cavity, $B_0$ | 2.75 T   |

3-D view of the multistage depressed collector is given in figure 1. To prevent radial shift of electron trajectories inside the collector in the absence of azimuthal magnetic field, a set of additional Helmholtz coils was used, creating quasi-homogeneous axial magnetic field over the whole length of the depressed collector. The azimuthal magnetic field is generated by the toroidal electromagnetic coil with azimuthal winding. Such winding produces azimuthally quasi-homogeneous magnetic field inside the electromagnet. On the front end of the electromagnet, the wires are tightly collected together in two “wisps”. In this way, we provided access for the electrons into the deceleration region, although the “wisps” create inevitable difficulties for transportation of electrons that will be discussed later in the paper. Also, the wiring on the outer wall can be made using wires of rectangular cross-section. Such form of the outer wires increases the uniformity of azimuthal magnetic field.

Four conical metallic electrodes (sections) serve for deceleration and collection of the spent electron beam. Their geometry was designed on the basis of numerical simulations of electric field distributions in the collector region. It should be noted that one of additional advantages of separation of electrons in the crossed fields is its stability to the secondary emission [14]. Most part of the electrons are collected by the outer walls of the sections, which excludes the possibility for the produced secondary electrons to pass to the gyrotron cavity. The minority of secondary electrons emitted from the sections’ tips is directed by the radial drift onto previous sections of the collector.

Figure 1. The model of 4-stage collector system.
The conical shape of the collector sections also secures tangential incidence of the primary electrons onto their surface, which additionally reduces thermal loads.

![Figure 2](image)

**Figure 2.** (a) Axial cross-section of the collector; (b) axial distributions of axial electric field $E_z(z)$ and potential $U(z)$ along the typical electron trajectory ($R(z) \approx 55$ mm in the collector region).

### 2.3. Field distributions

Distributions of electric field and potential were calculated during the collector system simulations to estimate the influence of electric field on the spent beam in terms of energy recovery and radial drift. The collector axial cross-section and the corresponding electric field distribution in the system along a typical electron trajectory are showed in figure 2. For this configuration, the electric potential changes linearly with coordinate, and the E-field is practically constant over the collector length.

Distributions of axial and azimuthal magnetic field components along a typical electron trajectory in the collector are shown in figure 3, (a). The azimuthal magnetic field in the volume of the depressed collector is quasi-homogeneous and provides successful separation of the spent electron beam. However, as it was mentioned previously, the presence of wire “wisps” creates a problem for the electron propagation to the depressed collector region. Local concentration of current creates strong local inhomogeneities of the magnetic field. Distribution of axial magnetic field near the wisps is shown in figure 3, (a), and a schematic illustration of electromagnet’s magnetic field distribution in the cross-section near the “wisps” is presented in figure 3, (b). Axial field distributions on both sides of the “wisp” were calculated. The wisps create a significant axial magnetic field of opposite polarities on different sides. The electrons which propagate on the side where the total axial magnetic field is increased (side with $+\alpha$ in figure 3, (b)) are additionally confined, which puts them into a different condition in the collector region. For these electrons, the radial drift distance will be too large for successful deposition on any of the collector sections, and they will be reflected back to the cavity, which can affect the generation efficiency of the gyrotron. For electrons propagating on the other side (side with $-\alpha$ in figure 3, (b)), the total magnetic field of the system of the electromagnet and coils...
change its direction because of the local magnetic field of the “wisp”. This change of field direction will rapidly increase their Larmor radii and cause these electrons to reflect back to the cavity as well.

A possible solution of the problem with local field inhomogeneity is simply to not allow electrons to propagate near “wisps”. It can be achieved by “trimming” the azimuthal parts of the beam which will potentially get in the local magnetic field. The analysis on the field distributions has shown (see figure 3) that the significant local magnetic field change is achieved on the total azimuthal angle of about 60° near the “wisps”. So, the azimuthal sections of this angle should be cut out to prevent the influence of this system drawback. In the simulation, the part of the electron beam yielding the above-mentioned reflections was cut out azimuthally. Propagation of the electron beam in this simulation is depicted in figure 4. As it can be seen from the figure, the radial drift separation works according to the theory. The simulation of such a cut-out HEB represents only a rough approximation of the suggested approach. Realization of this method can be achieved with implementation of a sectioned cathode emitter described, for example, in [20].

3. Conclusion
The performed numerical modeling and simulation of a 4-stage depressed collector system based on application of crossed azimuthal magnetic and axial electric fields have showed that practical implementation of multistage collectors is possible for pulsed gyrotrons, such as the experimental 74.2 GHz, 100 kW gyrotron of the SPbPU. Calculations of electron trajectories have already shown a possibility to achieve effective separation of electrons with different energies in the presence of typical
radial coordinate and velocity spreads of electrons. Drawbacks of the designed collector section are mainly associated with the presence of local magnetic field inhomogeneities induced by the “wisps” of wires. They can be solved via exclusion of azimuthal sectors of the spent beam determining the reflected electron flows. The designed collector system has already been constructed and being presently tested experimentally with the SPbPU gyrotron.

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