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EXPERIMENTAL STUDY OF A 110-GHz/1-MW GYROTRON WITH A SINGLE-STAGE DEPRESSED COLLECTOR

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The results of the experimental study of a gyrotron with a single-stage depressed collector are reported. Voltage retarding the electron beam was fed to the tube collector, and the dependence of the RF output power on the solenoidal magnetic field was recorded. A 1-MW output power was reached by increasing the gyrotron efficiency from 40 to 65% with a single-stage depressed collector.

1. INTRODUCTION

Until recently, an increase in gyrotron efficiency was associated mainly with an improvement in the electron-energy transfer of the RF field. The rated electronic efficiency of a gyrotron is fairly high and amounts to about 0.6. Similar values were reached in low-power experimental devices which used guns operating in the mode of weak spatial charge with a small spread of electron velocities [1]. However, the usual efficiency of high-power millimeter-wavelength gyrotrons is no more than 0.4, because of the decrease in rotational energy of the electrons. In gyrotrons, it is only this energy that is transmitted to the RF field, while the translational energy of the electrons, which is required for transfer of charge through the cavity, is almost unexpended. The relative part of the electron-gyration energy decreases both with increase in electron beam current and with increase in electron-velocity spread. An improvement of the efficiency in gyroscopic devices by taking off the electron-flow energy, unexpended in the interaction of electrons with the RF field was proposed back in 1967 in the patent for a "device for generation of electromagnetic oscillations at centimeter, millimeter, and submillimeter wavelengths" [2]. However, practical interest in this idea arose only in recent years and was associated with the use of gyrotrons in high-power applications, for example, in thermonuclear plasma heating.

The first theoretical estimates of energy recovery in gyrotrons were made in the late eighties. In [3], Gol'denberg et al. estimated the total efficiency of a gyrotron with energy recovery (or, gyrotron with collector potential depression (CPD) according to the foreign terminology) for the electron beam with a broad energy spectrum at the output of the interaction space, considered the possibility of spatial separation of electrons into energy groups in inhomogeneous magnetic fields, and tested the numerical calculation techniques for actual collectors. At present, the possibilities of increasing the efficiency of gyroscopic devices by using a CPD system are also being actively studied abroad. In all cases, researchers have used the scheme without separation of the electron beam into energy fractions, i.e., the scheme with a unipotential collector [4, 5]. The main results of gyrotron investigations abroad are presented in Table 1.

The objective of the studies performed at GIKOM and at the Institute of Applied Physics of the Russian Academy of Sciences in the field of CPD gyrotrons is the development of the theory and practical methods of calculation for such devices. In the present paper, we report on the first results of the experiments with a CPD gyrotron.

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Table 1

Company (country)	Frequency, GHz	Operating mode	Power, MW	Efficiency	Pulse duration, sec
KfK	140	TE10,4	0.5	0.48	0.03
(Germany)			0.46	0.51	0.2
NRL	155	TE12,4	0.35	0.27	0,005
(USA)	115	QO	0.43	0.13	0.00001
			0.2	0.16	0.00001
Toshiba	110	TE22,2	0.61	0.5	0.05
(Japan)			0.42	0.48	2.6
			0.35	0.48	5.0

2. BASIC CPD SCHEMES

The block diagram of a CPD gyrotron and its power supply switching is shown in Fig. 1. The collector is separated from the tube case by a long insulator and is grounded. The tube case is electrically insulated from the remaining elements of the scheme (in particular, from the cryogenic system). Two power sources are used to solve the problem of energy recovery. The parameters of the electron beam are determined by a source switched on between the cathode and the tube case. This source creates the total accelerating voltage U_a generating an electron beam with given parameters, but its power can be small, because of the small current fed to the tube case I_k ($U_a = 80$ kV, $I_k = 0.3$ A). The beam power is defined by a source of "low" voltage ($U_c = 50$ kV, $I = 30$ A) switched on between the cathode and the collector. The collector voltage must not exceed the reciprocal potential (which is usually about 30 kV), which corresponds to the minimum energy of electrons in the beam. When this value is exceeded, the number of reflected electrons increases abruptly, and, therefore, the current fed to the tube case also increases, thereby decreasing the efficiency and output power of the gyrotron. The efficiency of collector potential depression is proportional to the factor U_a/U_c. The total efficiency is determined by

$$\eta = \eta_{\text{out}} \frac{U_a}{U_c}, \tag{1}$$

where $\eta_{\text{out}} = P_{\text{out}}/IU_a$ is the output efficiency of the gyrotron without CPD, which is determined by the quality of the electron beam and the parameters of the electrodynamical system. The location of the insulator separating the collector from the tube case is determined by the design of the instrument and the desire to locate the insulate as near as possible to the beam deposition area, in the region of weak magnetic fields. Since the adiabatic invariant $W_\perp/B$ is conserved in gyrotrons, the smaller the magnetic field in the region of the electrostatic lens the better the fulfillment of the relation $V_\| \gg V_\perp$ and, therefore, the smaller the energy required for the electron to reach the collector. In this case, the number of reflected electrons is insignificant until high values of the retarding potential are reached at the collector, and this increases the gyrotron efficiency considerably.

A scheme in which the tube case is grounded and negative potential is supplied to the collector can also be used. The main difference of such a scheme is that the electrical insulation of the tube case from the cryogenic system is unnecessary here, which allows the volume of the heat-exhaust hole of the cryostat to be used most effectively.

Note that the decrease in energy of the electrons before they are settled on the collector considerably reduces heat loading in the electron-beam deposition area. The use of CPD schemes permits one, simultaneously with increasing the total efficiency of the system, to decrease heat loading on the collector and coolant consumption, which is also very important for high-power gyrotrons [6].

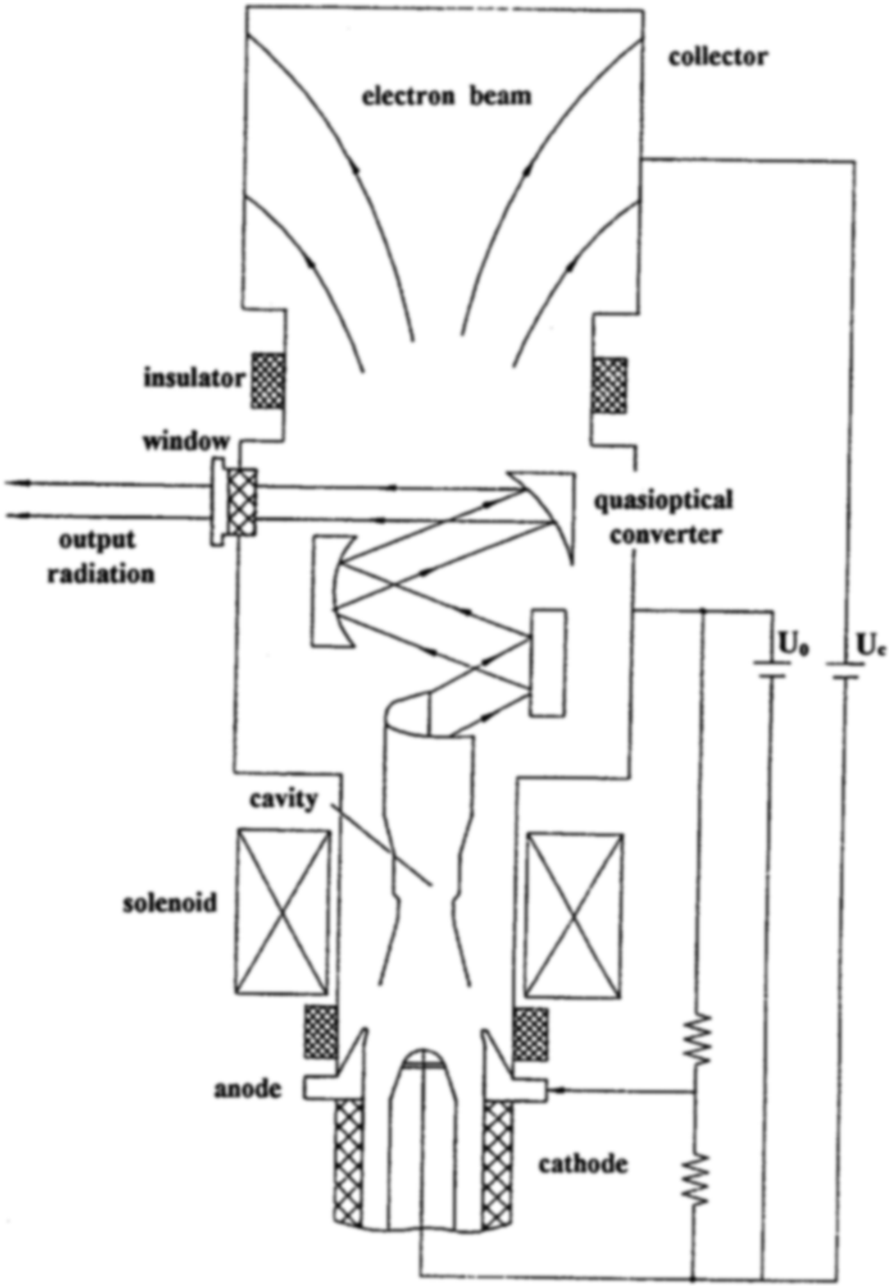

Fig. 1. Block diagram of a CPD gyrotron and its power supply switching.

3. EXPERIMENTAL FINDINGS

The simplest version of a depressed collector is the unipotential collector without separation of the electron beam into energy fractions. For experimental study of the CPD potential, we used a modified short-pulse prototype of a 110-GHz/1-MW/2-s gyrotron [7]. An insulator was placed between the collector and the tube case to create a retarding potential at the collector. The location of the insulator was determined by the design of the instrument. The insulator had size meeting electric resistance requirements and was mounted at the site of the flange connecting the case and the collector. The elevation of the collector caused displacement of the electron-beam deposition area compared with the calculated region, and this resulted in inhomogeneity of collector heating observed in the experiment. The main parameters of the experimental gyrotron shown in Fig. 2 are given in Table 2.

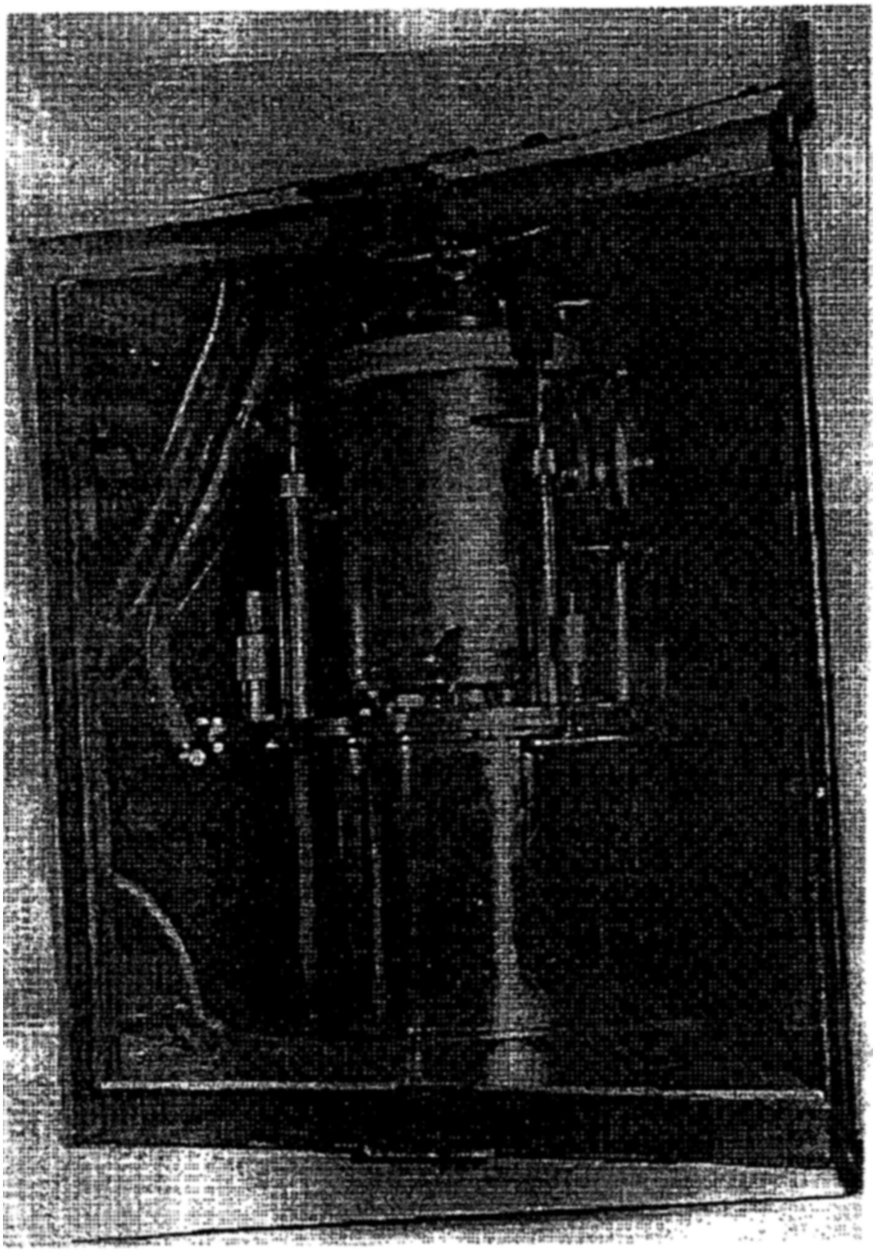

Fig. 2. The gyrotron with an insulated collector used in CPD experiments.

Table 2

Oscillation mode	TE 19,5
Operating frequency, GHz	110
Wavelength, mm	2.727
Output power, MW	1
Pulse duration, sec	0.0001
Accelerating voltage, kV	80
Maximum beam current, A	40
Cavity Q-factor	$\sim 10^3$
Ohmic loss density in the cavity, kV/cm^2	2.0
Pitch factor	1.3

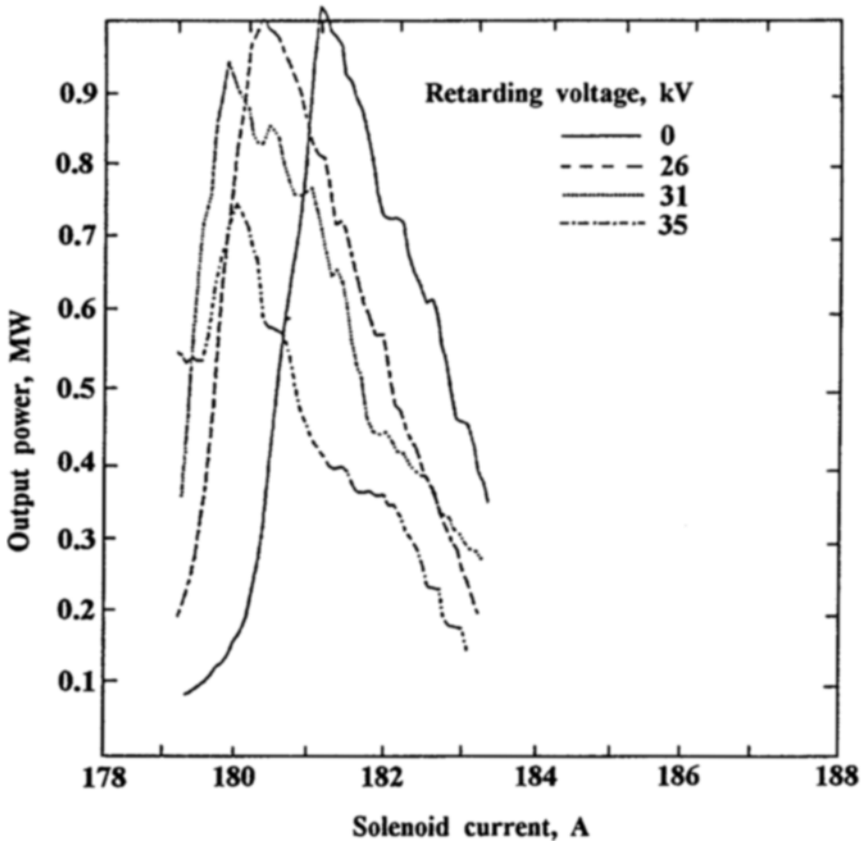

Fig. 3. Dependence of the output power on the solenoidal magnetic field for different retarding voltages.

In the model experiments, the collector voltage was generated by the electron-beam current controlled by the alternating resistance between the collector and the ground. We used an automated system based on a HiCom(DEC) computer and KAMAK apparatus [8, 9] to reach high accuracy. The measurements were performed in the mode of short pulses (100 μsec). The magnetic field was decreased gradually for fixed values of current and voltage to observe the dependence of the output power and efficiency on the magnetic field. The pulse duration of the accelerating voltage was determined by the power supplies. The power was measured by the calorimetric method. The values of the output power and efficiency were recorded on ADC buffers with given frequency. The data were saved to the disk for secondary processing and then were displayed. To increase the measurement accuracy and eliminate noise in the automated system, an ADC band selector was switched to fit the signal level.

The results of measurements of the output power as a function of the magnetic field (solenoid current) are presented in Fig. 3 for different collector voltages. The external parameters of the electron beam generation system were kept constant (70 kV, 30 A). The change of the magnetic field corresponding to the maximum output power with increase in retarding voltage had two causes. First, an increase in the potential depression due to reflected electrons with increased retarding voltage reduces the optimal magnetic field. Second, a change in the spatial charge distribution in the electron beam generation region due to reflected electrons can lead to a change in the electron-beam parameters in the interaction space and, finally, shift the maximum to either side. The first mechanism (depression of the potential) is more important for moderate retarding voltages. The change of the electron beam generation conditions appeared to be more significant for the maximum retarding voltage, and this caused displacement of the maximum power toward increased values of the magnetic field.

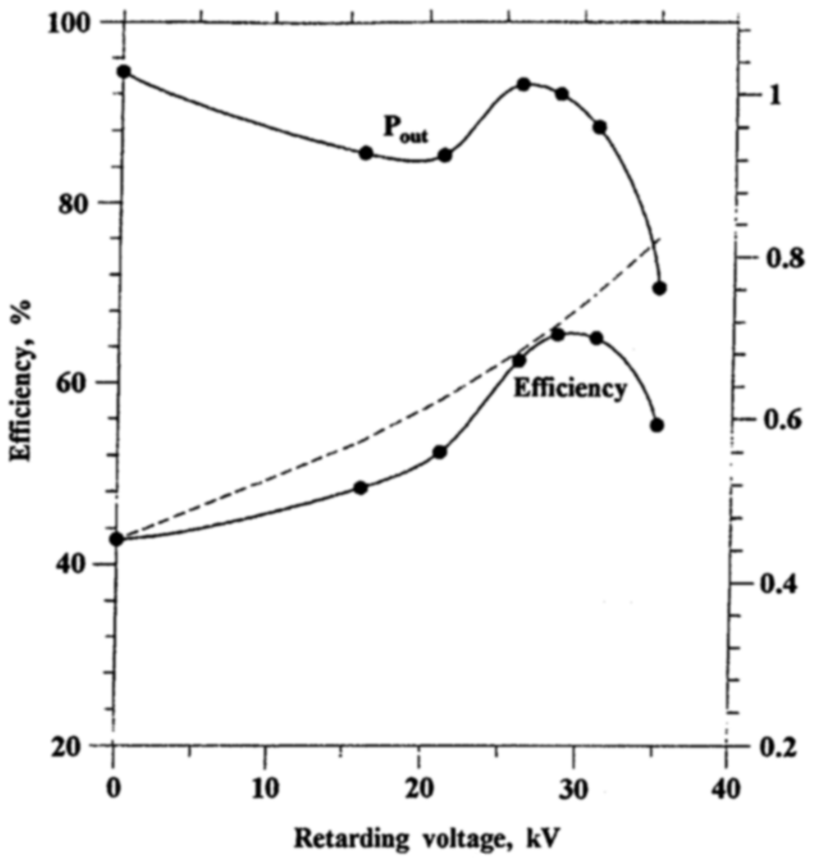

Fig. 4. Dependences of the output power and total efficiency on the retarding voltage.

The generalized results of these experiments are presented in Fig. 4 in the form of the dependence of the current supplied to the tube case on the retarding voltage. Under voltages considerably smaller than the reciprocal potential (minimum energy of electrons for which they are unable to overcome the retarding field), the experimental values of the efficiency agree with the values calculated by Eq. (1) (dashed line). For these voltages, the current fed to the case almost does not change and amounts to several tens of milliamperes. As the collector voltage increases, the number of reflected electrons and the current entering the case rise, reaching saturation, and then the efficiency and output power decrease abruptly. The current on the tube case increases by two orders of magnitude and can amount to several amperes. The efficiency reached in these experiments was 0.65 for an output power of 1 MW, which is obviously a challenging result at present.

Further increase in CPD efficiency can be reached by using multistage depressed collectors. In such systems, the electron beam is separated spatially into energy fractions, and each fraction is retarded by a collector of the corresponding potential. It was shown in [2] that the total efficiency of the system is determined by the expression

$$\eta = \frac{\eta_{\text{out}}}{1 - \sum_{i=1}^{n} \xi_i (1 - U_i/U_0)}, \tag{2}$$

where n is the number of retardation stages, $\xi_i = I_i/I_0$, I_i and U_i are the current and potential in the ith collector stage, I_0 is the total current of the electron beam, and U_0 is the cathode potential. In such systems, the part of the current formed by electrons with minimum energies must be fed to the precollector without retardation to avoid reflection of the electrons. The energy distribution of electrons at the output of the interaction space is being experimentally studied at present. The results of this experiment will be useful for the calculation of a collector with multistage potential depression. The creation of gyrotrons with efficiency close to unity is possible in this case.

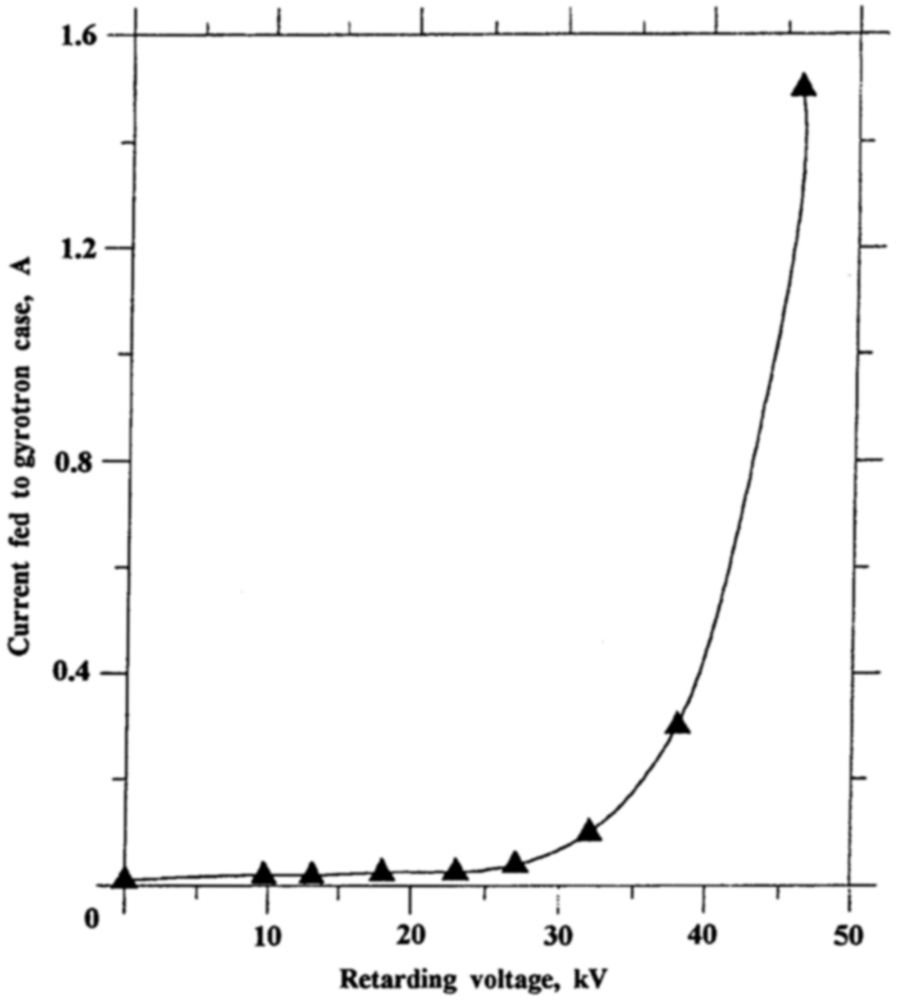

Fig. 5. Dependence of the current supplied to the tube case on the retarding voltage.

4. CONCLUSION

Using the results of these experiments, the following conclusions can be drawn:

- the scheme with single-stage CPD allows the gyrotron efficiency to be improved in a simple efficient way, including the cases where the initial efficiency is high,
- the total efficiency of a gyrotron with single-stage CPD, which we obtained experimentally, is 0.65 for output power near 1 MW.

Theoretical estimates (see, for example, [3]) show that the problem of reflected electrons can be solved by employment of multistage schemes with electron-beam separation into energy fractions. A further increase in the total efficiency of such a system is possible.

For a better understanding of CPD principles in gyrotrons, we plan to

(a) develop a special experimental gyrotron with an optimized collector and electric insulation of the tube case and cavity,

(b) continue the experimental study of a gyrotron with insulated case operating in the mode with two independent power sources, perform experiments in the long-pulse mode, etc., and

(c) study the power spectrum of the electron beam at the output of the interaction space to develop a gyrotron with a multistage depressed collector.

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