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DEVELOPMENT OF A HIGH-POWER PULSED SUBTERAHERTZ GYROTRON FOR REMOTE DETECTION OF SOURCES OF IONIZING RADIATION

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We describe the main stages of the development of a gyrotron in the sub-terahertz band with a power of several hundreds of kilowatts, a duration of the output radiation pulses of about 10 μs, and the generation frequency corresponding to an atmospheric transparency window. The gyrotron having a working frequency of 0.67 *THz, a power of* 200–300 *kW, and the focal diameter of the output beam* 1–2 *mm can be used to detect sources of ionizing radiation from a distance of several tens of meters. The detection principle is based on the appearance of a microwave frequency discharge in the focal spot if the number of free electrons exceeds the natural background by* 1–2 *orders of magnitude. The electron-optical system of such a gyrotron has been calculated and optimized. The scenario of the gyrotron switch-on has been analyzed for the electron beam formed in such a system, and the possibility of stable single-mode generation on the* $TE_{31.8}$ *mode is demonstrated. The results of analysis of thermal loads, which demonstrate their acceptable level in the cavity and the tube cavity for pulse durations of about 10 μs are presented.*

1. INTRODUCTION

Creation of high-power terahertz-wave generators is of interest for many applications, see, e.g., [1–4]. One of such applications is remote detection of hidden radioactive sources [5, 6]. In this domain, the most promising generator of the radiation in the terahertz spectral region is the gyrotron, whose power exceeds the conventional backward-wave oscillators and semiconductor sources by several times, and the cost, dimensions, and operating voltages are significantly lower than those of free-electron lasers. The techniques of production of superstrong pulsed magnetic fields allow one to generate high-power gyrotrons which produce pulses with durations of several tens of microseconds in the subterahertz frequency range. In order to reduce the energy output ratio, the dimensions of the solenoids in the gyrotrons with pulsed magnetic field should be as small as possible. This requirement is limited only by the condition of a sufficient size of the solenoid for installation of the electrodynamic system of the device. Miniaturization of the opening of the solenoid and the desire to retain the symmetry of the design elements result in the necessity to use external convertors of the radiation into narrowly directed wave beams, which is a distinctive feature of gyrotrons with pulsed magnetic fields. Another significant difficulty for the developers of such devices is sharp compression and decompression of the electron beam, which is caused by the small dimensions of the solenoid and, consequently, the nonadiabatic character of the electron-optical system of the electron beam

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formation. Finally, it is difficult even to generate an intense magnetic field and ensure the penetration of the variable magnetic field through the metal body of the device.

This paper analyzes the requirements imposed on the source of the electromagnetic field of microwave frequency, which allows one to detect the presence of ionizing radiation from a sufficiently long distance of several tens of meters (see Sec. 2), and the methods of solving of the above-specified problems which take place during the development of such a gyrotron-based source. Section 3 describes specific features of the electron-optical system of a subterahertz gyrotron, which makes it possible to form a tubular electron beam with a small velocity spread, radii R of the guiding centers of the electron orbits, and a high fraction of the electron rotation energy, such that a relatively high efficiency can be achieved. Section 4 considers the gyrotron switch-on scenario and presents the results of calculations of its efficiency and output power. Section 5 evaluates thermal loads on the structural elements of the device. The results of experimental studies of the magnetic system are presented in Sec. 6. The main results of the calculations are formulated in the Conclusions.

2. MAIN REQUIREMENTS IMPOSED ON THE GENERATOR OF A MICROWAVE ELECTROMAGNETIC FIELD FOR REMOTE DETECTION OF SOURCES OF IONIZING RADIATION

2.1. Remote-detection principle

Recently, an idea has been advanced about the possibility to use a high-power electromagnetic field of the microwave spectral region for remote detection of sources of ionizing radiation [6]. Its essence is that when focusing a high-power electromagnetic field into a sufficiently small volume, one can achieve the conditions under which its amplitude exceeds the breakdown value. In this case, the presence of a free electron in the field localization region results in a microwave discharge. The terahetz frequency range is singled out due to the fact that the electromagnetic field with the frequency belonging to this range can be focused in a sufficiently small volume. The characteristic size of this volume is determined by the wavelength, for which the probability of appearance of free electrons required for the initiation of a microwave discharge is negligibly small for the natural ionization background. In this situation, the occurrence of a discharge will indicate the presence of sources of the ionizing radiation. Since for a sufficiently long pulse, the possibility that a free electron will reach the microwave field localization region is higher, there is a limitation for the duration of the microwave pulse. This time can be estimated rather easily for the simplest model, but for more realistic ones, the problem is much more complicated. This distinguishes the considered situation from the discharges in focused beams of a lower-frequency electromagnetic field, where free electrons are almost always present in the focal spot, or the discharges, which are initiated by the optical radiation, when the use of high-power lasers allows for multi-photon ionization of neutral atoms in the absence of free electrons in their initial state.

2.2. Requirements imposed on the microwave source

As it has been already noted, sources of terahertz waves with powers of tens and even hundreds of kilowatts can be required for some applications. Thus, an increase in the power of the existing generators in this spectral region is important from the viewpoint of not only general physics, but also practical applications. Specifically, for the electromagnetic-field amplitude to exceed the threshold values of the discharge occurrence, the radiation with power over 100 kW should be focused in the aperture with a characteristic size of about 1 mm. When choosing the radiation frequency, it is natural to take into account one of the atmospheric transparency windows to minimize the loss when the microwave beam passes from the output window of the tube to the focusing region. Basing on the objective of having a sufficiently high radiation frequency, i.e., a sufficiently small volume of the focused field, as well as an acceptable loss during transmission from the radiation source to the studied object, we chose a frequency of 0.67 THz, for which the characteristic loss in air is approximately 50 dB/km. It should be emphasized that there is some characteristic duration of a microwave pulse, for which the discharge is initiated not due to the diffusion of the free electrons of the natural background into the field localization volume, but due to the free electrons, which are produced as a result of the presence of a source of ionizing radiation. For the above-specified size of the localization regime, this duration is equal to approximately 10 μs. Basing on the evaluations of the conditions for the discharge occurrence, which were described in detail in [7, 8], we will restrict our consideration to the statement that a gyrotron with an operating frequency of 0.67 THz and a power of 200 kW can be used for remote detection of radiation sources that produce the amount of free electrons, which exceed the natural background by more than 20 times from a distance of 20–30 m [8], provided that the radiation is focused into a focal spot with a diameter of 1 mm.

2.3. Available stock

The first experiments with subterahertz-band gyrotrons based on pulsed solenoids were described in [9]. In the frequency range 0.3–0.7 GHz and for a pulse duration of about 50 μs, a power of about 100 kW was obtained, specifically, 130 kW at a frequency of 0.33 GHz and 40 kW, at 0.65 THz. Later, in 2006-2009, upgrade of pulsed solenoids allowed one to achieve a generation frequency above 1 THz at a kilowatt output-power level under the conditions of resonance with the fundamental cyclotron harmonic [10], which simplifies significantly the problem of mode selection and, in the long term, allows one to ensure a high power of the generated radiation. The possibility of stable excitation of one working higher mode was demonstrated in continuous-wave gyrotrons with a megawatt power level and operating frequencies of 170 GHz, which were developed for the ITER tokamak [25]. Specifically, acceptable ohmic losses and, consequently, high excitation efficiency, were demonstrated at the $TE_{31.8}$ mode [19, 20], which made it a possible oscillation type for a high power subterahertz-band gyrotron.

Thus, a gyrotron with an output power of 200–300 kW, a pulse duration of 10 μs, and an operating frequency of 0.67 THz should be developed for the detection of ionizing-radiation sources. The main elements of the corresponding gyrotron and its magnetic system will be described in the following sections.

3. THE ELECTRON-OPTICAL SYSTEM OF A SUBTERAHERTZ-BAND GYROTRON BASED ON A PULSED SOLENOID

The transition from the millimeter wavelength band to the submillimeter one imposes a set of specific requirements on the electron-optical system of the gyrotron. It is known that the most important parameters of a helical electron beam are the average pitch factor g, i.e., the ratio of the electron rotation velocity and the velocity of their translational motion, and the spread $\delta v_\perp$ of the electron rotation velocities. The increase in the pitch factor results in an increase of the gyrotron efficiency, and the limiting achievable pitch factor is determined by the requirement of stability of the electron beam. The most important factor that limits g is the loss of stability of the helical electron beam, which is caused by the reflection of part of the electrons, which have the highest oscillatory velocities, from the magnetic mirror and their further trapping in the adiabatic trap between the cathode and the cavity input. It is evident that the probability of such trapping increases rapidly with increasing spread of their velocities. Therefore, the maximum value of the pitch factor turns to be directly connected with the problem of minimization of the velocity spread. Elementary estimations show that the limiting value of g, in accordance with [11], should not exceed

$$g_{\max} = \frac{1}{\sqrt{k\,\delta v_\perp}}, \qquad (1)$$

where the empiric coefficient $k \approx 1.0$–1.5. The spread of electron rotation velocities in the helical electron beam is caused by a set of reasons, specifically, a possible violation of the axial symmetry, the presence of the positional spread of velocities due to the difference in the points of electron exit from a finite-width emitter, nonadiabatic fields in the transition region between the gun and the cavity, azimuthal nonuniformity of the emission, roughness of the emitter, and, finally, the field of the space charge of the beam, which determines the partial velocity spread $\delta v_{\perp\rho}$ [12].

The influence of some of the reasons can be weakened by adjusting the electron-optical system, applying a certain technique of the emitter manufacture, and optimizing the shape of the electrodes of the magnetron-injection gun. However, the electron trajectories become increasingly small-scale as the wavelength of the output radiation decreases, which results in a greater role of the emitter roughness. In the subterahertz frequency range, the contribution made by this factor exceeds, as a rule, the perturbation of the velocity distribution, which is produced by the field of the space charge of the beam. The partial spread of the velocities, which is caused by the emitter roughness, can be evaluated from the relation [13]

$$\delta v_{\perp \mathrm{rh}} = 1.6\sqrt{\left(1+\frac{\pi^2}{4}\tan^2\varphi\right)\frac{r_0}{h}}. \tag{2}$$

Here, r_0 is the size of the roughness, h is the elevation of the electrons over the emitter, and φ is the inclination angle of the magnetic field with respect to the emitter surface.

Preliminary estimation of the gyrotron efficiency shows that in order to achieve the required power of several hundreds of kilowatts, one should have an operating current of 15 A, an electron beam voltage $U_0 = 70$ kV, and a pitch factor $g \approx 1.2$, whereas the difference in the positioning of the guiding centers of the electron orbits in the cavity must not exceed 0.3 of the radiation wavelength. According to the conclusions made in [14], the negative influence of the positioning spread is not so significant up to the above-specified value, and the decrease in the efficiency amounts to no more than 10% of the maximum possible value. The radius $R_0 = 2.3$ mm of the electron beam in the cavity ensures the most favorable conditions for the excitation of the $TE_{31.8}$ at a frequency of 0.67 THz for the cavity radius $R_\mathrm{p} = 4.54$ mm. The shape of the electrodes of the electron-optical system and the electron trajectories are shown in Fig. 1.

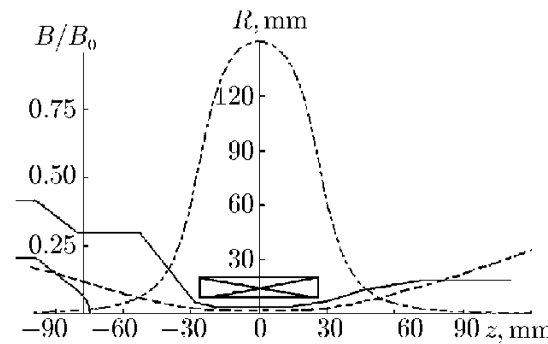

Fig. 1. Outline of the magnetic and electrodynamic systems of the gyrotron, the longitudinal distribution of the magnetic field (the dash-dot line), and the trajectories of the guiding centers of the electron orbits (the dashed line); $B_0 = 27.522$ T, $U_0 = 70$ kV, and $R_0 = 2.3$ mm.

The main features of the electron optical system are as follows:

(i) the off-axis character of the magnetic field decreases significantly the reliability of parameter calculations of the magnetron injection gun, which are based on the adiabatic theory [15] and used usually for preliminary estimations;

(ii) the gap H between the cathode and the anode is large in the diode version of the gun ($H/R_\mathrm{c} \sim 1.8$, where R_c is the cathode radius), which complicates the process of minimization of the partial positioning velocity spread;

(iii) the ratio between the working current of the magnetron injection gun and the Langmuir current is great ($I/I_\mathrm{L} \sim 0.2$), which increases the dependence of the pitch factor and the velocity spread on the beam current;

(iv) the emitter width L is great on the scale of the electron elevation h ($L/h \approx 10$), which results in the nonuniform shielding of the electric field on the emitter by the Coulomb field of the beam with the corresponding decrease in the pitch factor and the increase in the velocity spread.

Numerical optimization of the shape of the electrodes for a cathode radius of 22 mm, which was based on the methods described in [11], allowed one to achieve the following parameters of the electron beam in the model with no allowance for the emitter roughness: $g = 1.27$ and $\delta v_\perp = 0.09$ for the beam current $I = 15$ A. A displacement of the cathode along the tube axis, which is possible due to variations in the electron beam radius in the cavity of the dismountable tube version or to the thermal shift of the design elements, does not result in a significant variation in the electron beam parameters, namely, for a cathode shift of 1 mm towards the cavity for the equal beam current $I = 15$ A, $g = 1.22$ and $\delta v_\perp = 0.10$, whereas for a cathode shift of 1 mm away from the cavity, $g = 1.26$ and $\delta v_\perp = 0.05$. The parameters of the electron beam for the above-specified geometry of the electrodes with minor variations of the region near the emitter were studied using the numerical codes EGN2W and MICHELLE [16]. All the results of the numerical simulation yield similar values of the velocity spread (about 10%) and the pitch factor (1.1–1.3) neglecting the emitter roughness. "Sagging" of the potential in the cavity is about 1.7 kV and does not influence significantly the operation of the electron optical system.

As it has been mentioned above, the roughness of the cathode surface plays a rather important role in the formation of the electron beam in the gyrotrons of the short-wave spectral band. By substituting the angle φ of the inclination of the magnetic field to the emitter surface and the electron elevation h in the gun into Eq. (2), one can easily estimate the electron velocity spread for different roughness sizes r_0. Specifically, for the roughness size equal to 10 μm, the velocity spread is $\delta v_\perp = 0.36$, and for that equal to 20 μm, $\delta v_\perp = 0.50$. The numerical simulation was performed for moderate roughness of 10 μm. The calculations show that the electron velocity distribution function remains single-mode and close to the Gaussian up to the maximum working current of the beam, 15 A. However, one should note a very high value of the reflection coefficient R_{ref} of the beam from the magnetic mirror, which reaches 0.05 for a current of 10 A. At the same time, the results of theoretical analysis of the transitional processes in the magnetron injection guns of gyrotrons, as well as a series of experimental measurements of the parameters of the helical electron beam [17, 18] show that it is desirable to limit the value of $R_{\rm ref}$ at a level of 0.02–0.03 to ensure its stability. This requires a technique of emitter manufacture, under which the roughness size would not exceed 2 μm significantly. For preliminary estimates, we manufactured a cathode of LaB_6, whose emission properties allow for a short-term deterioration of vacuum and an increase in pressure up to the atmospheric one, which makes it possible to replace individual elements in a demountable tube and, e.g., optimize the length and profile of the cavity without replacing the cathode unit. In the process of measuring the cathode parameters, we recorded a nearly uniform distribution of the temperature over the emitter surface (the maximum temperature difference was about 20 °C) and the required temperature 1500°C for the heating source with a power of about 500 W, which amounts to about 70% of the maximum value.

4. CALCULATION OF THE OUTPUT PARAMETERS OF THE GYROTRON AND ANALYSIS OF THE SCENARIO OF STABILIZATION OF THE WORKING GENERATION REGIME

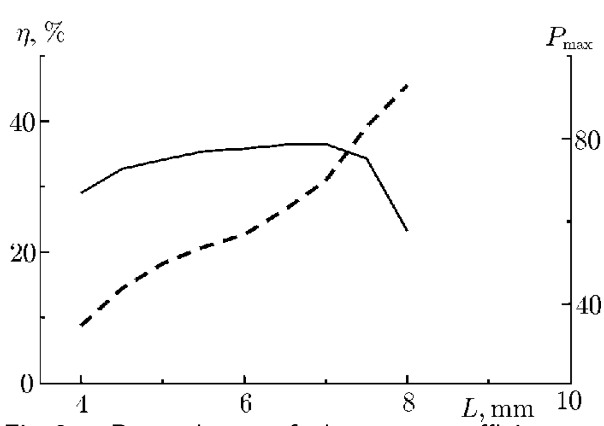

Fig. 2. Dependence of the output efficiency η (solid line) and the maximum power density $P_{\rm max}$ at the cavity wall (dashed line) depending on the length L of the cylindrical part.

The working gyrotron mode was selected after analysis of the spectrum of the eigenmodes of the circular waveguide allowing for the available experimental data. When studying the regime of generation of the working $TE_{31.8}$ mode (see Fig. 2) and analyzing the scenario of oscillation excitation (see Fig. 3), we considered a cylindrical cavity of circular section that had a supercritical cathode narrowing with an angle of 4° and an output widening with an angle of 2.5°. A smooth transition was installed behind the cavity, and the transition profile was optimized in order to minimize the transformation of the working mode. According to the calculations, in the developed output transition, the power loss of the working mode due to reradiation into other modes amount to approximately 0.05.

The scenario of the gyrotron switch-on and operation start is determined by the transition processes at the leading edge of the accelerating-voltage pulse. The analysis of the starting currents and the solution of the self-consistent system of equations, which consists of the electron motion equation and the equations that describe the changes in the amplitude and phase of the interacting modes, indicates that, allowing for the variation of the pitch factor at the leading edge of the pulse, the starting currents for the generation of the working and spurious modes exceed the starting current of the beam calculated by the current-voltage characteristic for a voltage below 40 kV. Basing on this fact, the excitation scenario was calculated from a voltage of 40 kV to an operating voltage of 70 kV with a step of 5 kV. At each voltage value, the calculation was performed until the stationary generation regime became stable. As we passed over to the next voltage value, the stationary amplitudes of the modes were specified as the initial conditions, and the values of the pitch factor, velocity spread, and the corresponding dimensionless parameters of the self-consistent system of equations were recalculated with respect to the corresponding voltage value. Leaving the calculation of the current-voltage characteristic outside the scope of this paper, since it is a separate, rather interesting problem, which will be presented in a separate paper, we only state that it consists of two intervals corresponding to the current limitation by the space charge in the case of low anode voltages, where the parameters of the electron beam were determined analytically, and the temperature limitation of the emission in the case of high voltages, where the beam parameters were calculated using the numerical-simulation code EPOS [11]. The values obtained by numerical simulation of the electron optical system were used as the parameters of the electron beam for an operating voltage of 70 kV. Note that as the voltage grows from 20 to 70 kV, which corresponds to the cathode operation in the regime of temperature limitation of the emission current, the beam current in the analyzed magnetron-injection gun increases due to the Schottky effect by only 0.5 A. Analysis of the starting currents shows that the $TE_{30.9}$ mode has the lowest starting current for an operating magnetic field of 26.5 T, but the numerical simulation allowing for the mode competition in the multimode cavity [21] showed that the $TE_{32.8}$ mode is excited in the competition process and suppresses the excitation of other modes. As the voltage increases up to 60 kV, the oscillations of the specified mode are quenched, and the working $TE_{31.8}$ mode is excited (see Fig. 3).

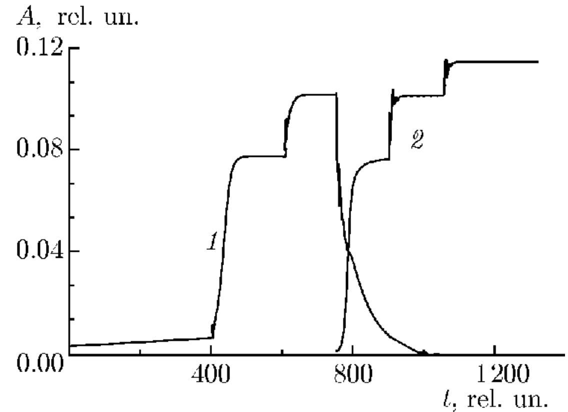

Fig. 3. Scenario of stabilization of the operating generation regime at the leading edge of the accelerating-voltage pulse. A is the mode amplitude, the operating frequency of the gyrotron is 670 GHz, $L = 5$ mm, 1 relative time unit is equal to 1/13 ns. Curves *1* and *2* relate to the $T+_{32.8}$ mode and $T+_{31.8}$ mode, respectively. The horizontal sections of curve *1* correspond (left to right) to the accelerating voltages 45, 50 and 55 kV, and those of curve *2*, to 60, 65, and 70 kV.

The cavity was optimized with respect to the length of its cylindrical part in order to achieve the maximum efficiency at the following parameters of the electron beam: an accelerating voltage of 70 kV, a beam current of 15 A, a pitch factor of 1.3, and a velocity spread of 0.3. The maximum electron efficiency $\eta_{\max} = 0.36$, i.e., gyrotron efficiency with no allowance for the ohmic loss, which according to the estimates, amount to less than 10% of the useful diffraction loss, and the loss to the working-mode conversion into a narrow wave beam, was achieved at the length of the cylindrical part of the cavity $L = 7$ mm, see Fig. 2. However, at such L the ohmic loss increased considerably. In this case, it seems reasonable to limit the length of the uniform interval by the value 4–5 mm, since in this parameter region, the efficiency is little different from $\eta_{\max}$, and the ohmic loss is low. Calculations showed that the dependence of the optimal length on the pitch factor is weak, and even when it decreases to 1.1, the gyrotron efficiency can reach 32% [22].

5. THERMAL CALCULATION

The maximum admissible pulse duration determined by the thermal loads in the cavity and the collector was evaluated by means of the ELCUT code [23]. In accordance with the estimates [6–8], the

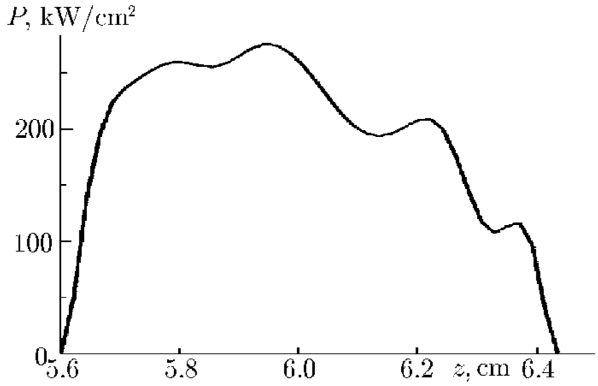

Fig. 4. Distribution of the power density P along the collector. The z coordinate is counted from the center of the cavity.

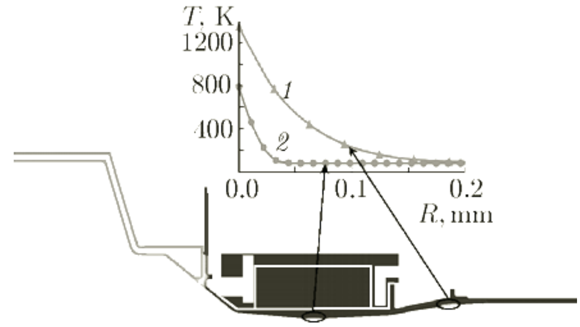

Fig. 5. Temperature distribution over the radial coordinate for the cavity and the collector. $z = 0$ is the center of the cavity (see Fig. 1). Curve *1* corresponds to the collector located at $z = 85$ mm, and curve *2*, to the cavity.

gyrotron will operate in the generation regime with a pulse duration of 10 μs. Since the gyrotron operates in the single-pulse regime, and the solenoid, the stainless-steel body and the collector of the gyrotron are cooled with liquid nitrogen, the temperature of liquid nitrogen ($T_{\rm N}$) was chosen as the initial temperature of the structural elements. To increase the current landing area, the gyrotron collector is made as a cone of a heat-resisting material (molybdenum) with an average radius of 10 mm, whose envelope makes an angle of about 5° with the magnetic-field line. The calculation of electron trajectories yields the length of the trace on the collector being equal to about 8 mm, and the load distribution in this case was rather uniform (see Fig. 4). The nonstationary problem for determination of the maximum temperatures of the collector and the cavity in the pulsed gyrotron operation regime was solved for the pulse duration τ up to 50 μs. One can evaluate the temperature T for shorter pulses by assuming that $T \propto \sqrt{\tau}$.

The results of the corresponding calculations are shown in Fig. 5. The obtained values of the maximum temperature in the single-pulse regime do not exceed the values, which allow long-term operation of the device in the cyclic regime "heating—cooling" and "expansion—compression" without destruction of the structural elements [26], including the case of the absence of generation, where all energy of the beam is released at the collector.

6. EXPERIMENTAL STUDY OF THE PULSED SOLENOID

It is well known that the problem of selective excitation of the working mode is simplified in the case of operation at the fundamental gyrofrequency harmonic. In the overwhelming majority of cases, the choice of higher harmonics is caused by the impossibility to produce magnetic fields that would be sufficiently strong for operation at the fundamental cyclotron resonance. Modern cryomagnet systems allow one to produce fields up to 20 T, and hybrid magnetic systems are bulky and energy-consuming. Thus, the use of pulsed solenoids is almost a unique method for creation of the magnetic field amounting to 27–28 T, which is required for operation at the fundamental cyclotron resonance.

To reduce the energy of the magnetic field, the wire was wound directly on the tube body and the liquid-nitrogen cooling was used, which allowed us to achieve an additional thermal stabilization of the structure and reduction of the ohmic loss. Mechanical stability was achieved by embedding the winding in epoxide compounds and installation of an external fiber-glass casing. The working bore of the solenoid wound with a copper wire was equal to 14 mm, and the body had stainless-steel walls with a thickness of 1 mm. The measured inductance amounted to 320 μH for a solenoid constant of 3.5 T/kA. The solenoid constant was measured with a Hall sensor for the case of a d.c. current of about 10 A. During the tests of the solenoid prototype in the regime of single pulses (1 pulse per three minutes), a magnetic field of 28 T

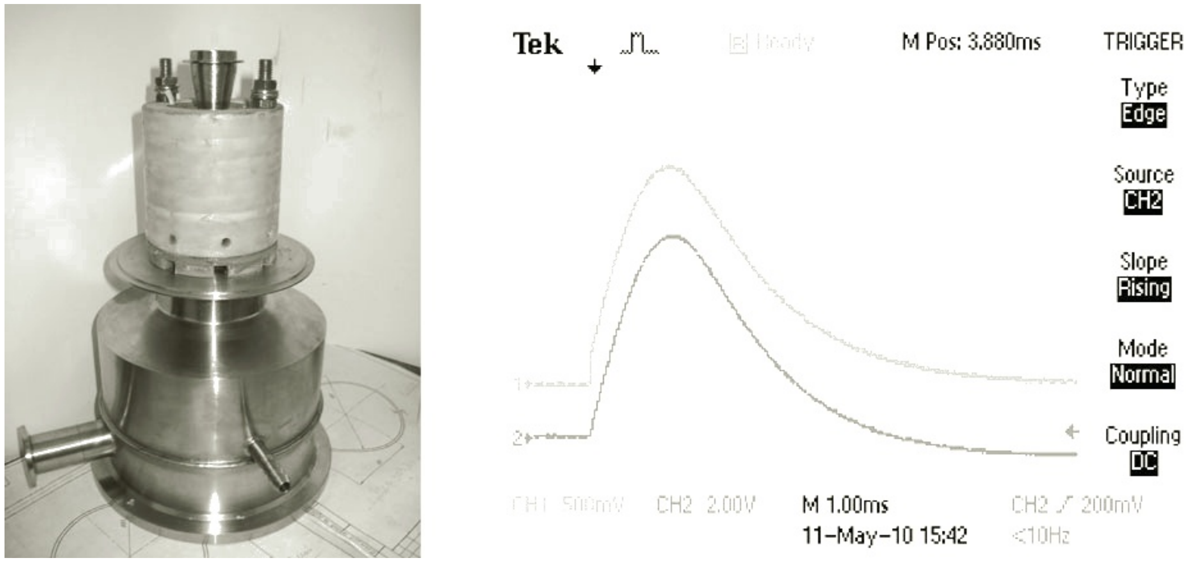

Fig. 6. Body of the gyrotron with the wound solenoid and oscillograms of a pulse of the current through the solenoid, which was obtained by using a 75 mV/300 A shunt (top curve) and a 1 V/1 kA Rogovsky belt (bottom curve).

was obtained for a current of 8 kA. One should note low consumption of the coolant, specifically, 3 liters of liquid nitrogen were sufficient for several tens of pulses. A photo of the gyrotron body with a wound solenoid along with the oscillogram of a solenoid current pulse are shown in Fig. 6.

By this moment, the main units of the gyrotron have been manufactured. The experimental studies of the device are scheduled for November–December 2011.

7. CONCLUSIONS

The calculations performed demonstrate the possibility to produce a gyrotron with an output power of 100–200 kW, an operating frequency of 670 GHz, and an efficiency of 25–30%. This gyrotron will be used for remote detection of ionizing-radiation sources from a distance of 20–50 m. A solenoid with a magnetic field of 27–28 T, which operated in the single-pulse regime and had a sufficient internal volume for installation of an electrodynamic system of the gyrotron with specified operating frequency, has been tested successfully.

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