TERAHERTZ LARGE ORBIT GYROTRON AND GYROTRINO AS ALTERNATIVES TO CONVENTIONAL GYROTRONS

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Abstract

THz gyrotrons have proven to be in high demand as sources of the medium power for the development of high-field magneto-resonance spectroscopy and diagnostics of various media. However, despite impressive achievements in this field, very few spectroscopic and diagnostic devices are equipped with THz gyrotrons. This circumstance is mainly due to the complexity and high cost of such generators, for which superconducting solenoids with a strong magnetic field in a large volume are required. A significant mitigation of this problem can be achieved by using the so-called Large Orbit Gyrotron (LOG) and gyrotrino. Operation at higher harmonics in a LOG or placement of a gyrotrino inside a spectrometer cryomagnet enable greatly simplify THz systems of ESR and DNP-NMR spectrometers. At the Institute of Applied Physics of Russian Academy of Sciences, a powerful third-harmonic generation has been obtained in 1-THz and 0.394-THz LOGs at significantly lower magnetic fields than in conventional gyrotrons. To test the feasibility of the developed fundamental-harmonic 0.264-THz gyrotrino, a CW generation at the required low voltage of 1.5 kV was demonstrated in the existing second-harmonic gyrotron originally designed to operate at a much higher voltage.

1. INTRODUCTION

Having a long history LOGs [1-6] differ from conventional gyrotrons only by the shape of the electron beam. Axes of the helical trajectories lie relatively far from the axis of axi-symmetric cavity (hollow beam) in conventional gyrotrons and in a close vicinity of it (encircling beam) in LOGs. Due to using an encircling electron beam, a LOG provides a higher selectivity because only azimuthally rotating modes with the azimuthal index equal to the number of the resonance cyclotron harmonic can be excited in it. This is especially important when operating at high cyclotron harmonics. In experiments with moderate relativistic beams, we obtained a powerful selective generation up to the fifth cyclotron harmonic. However, such sources are fairly complex and in addition the frequency gain in them is not too large due to decrease of the electron cyclotron frequency with electron energy. Using the beams with lower, sub-relativistic voltage we obtained a powerful generation with a high frequency gain at the third cyclotron harmonic at a frequency of 1 THz and 0.39 THz (the latter frequency is typical for EPR and DNP-NMR spectrometers). The corresponding operating magnetic fields in these oscillators were significantly lower than in conventional gyrotrons of these frequency ranges operating at lower harmonics. According to simulations, a modification of cavity can enable an operation at the fourth harmonic and thereby at higher radiation frequencies or/and lower fields. The possibilities of LOGs are discussed in Section 2.

The idea of gyrotrino [7] is based on the proximity of the electron cyclotron frequency in a gyrotron to the frequency of the paramagnetic resonance in a sample under study in the same magnetic fields. However, exact frequency matching the gyrotron and EPR frequencies in this case can only be provided at an operating gyrotron voltage of 1.5-2 kV. This makes possible to place the gyrotron with such an extremely low voltage (we name such oscillator “gyrotrino”) into the spectrometer and thereby eliminate the need for an additional superconducting magnet and a long THz transmission line with high losses. Necessity of frequency matching and a restricted space in the cryomagnet bore cause specific features of gyrotrino design. An alternative version of the gyrotron inside the spectrometer magnet [8] can be based on changing the value of spectrometer magnetic field in the region of the oscillator. The feasibility of the low-voltage generation was examined using an existing CW gyrotron initially designed for operation with a relatively high voltage [9]. The problems of gyrotrino implementation are considered in Section 3.

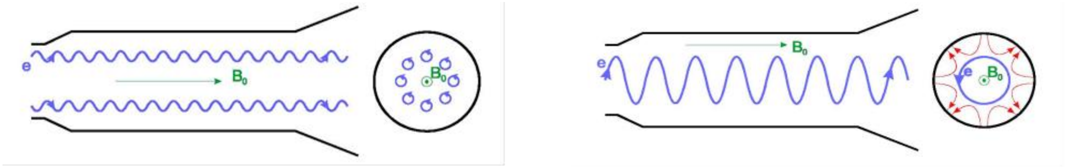
2. HIGH-HARMONIC OPERATION IN LARGE ORBIT GYROTRONS

At relatively small transverse dimensions of the cavities, it is possible to obtain an efficient single-mode generation in conventional gyrotrons not only at the fundamental cyclotron resonance, but also at the second cyclotron harmonic. The situation changes radically when trying to generate at a high harmonic with the number $s > 2$ to reduce the operating magnetic field and advance to higher frequencies. At sub-relativistic electron velocities, the weakening of the coupling of the operating wave with the beam and strong competition from modes excited at low cyclotron harmonics lead to the necessity of using in this case additional methods of electrodynamic and/or electronic mode selection. The coupling of electrons with waves at high harmonics at relativistic electron energy can be equal to or even stronger than at the fundamental resonance, but complex problem arise in the discrimination of neighboring harmonics. In addition, as above already mentioned, using relativistic energies simultaneously decreases the cyclotron electron frequency and frequency gain.

The selectivity of high-harmonic generation can be significantly increased at sub-relativistic electron energies by using a central injection into a gyrotron cavity of a thin mono-axial beam with helical electron trajectories, which surround the axis of an axially symmetric cavity, instead of a conventional hollow poly-axis electron beam (Fig. 1) [1-6]. Being injected along the cavity axis, an axis-encircling beam can excite only co-rotating TE_{mp} modes whose azimuthal indeces m are equal to the number of the resonant cyclotron harmonic s. This strong selection rule leads to a rarefying of the spectrum of the dangerous modes and makes it possible to operate at higher harmonics, allowing the THz range to be reached. The name "Large Orbit Gyrotron" is used since such devices can operate at higher harmonics and, consequently, at a smaller magnetic field and a larger electron Larmor radii than a conventional ("low orbit”) gyrotron with the same frequency (Fig. 1). If the conventional gyrotron and LOG operate at the same harmonic, then the electronic "orbit" in them is naturally the same.

The strong mode selection in a LOG can be explained by considering of a one electron rotating with a cyclotron frequency $\omega_B = eB_0 / m_e \gamma$ along the Larmor circle in a homogeneous magnetic field $\vec{B}_0$

$$x = r\cos\omega_B t,\ \ y = r\sin\omega_B t \qquad (1)$$



a) b)

Fig. 1. Electron beams in conventional gyrotron (a) and high-harmonic LOG (b).

and interacting with a wave field (Fig. 2a). Here, -*e*, m_e, $r = v_\perp / \omega_B$, and $\gamma = (1-\beta^2)^{-1/2}$ are the charge, mass, Larmor radius, and the Lorentz factor of the electron, $v_\perp = \beta_\perp c$ is its rotational velocity, *c* is the speed of light. Let us consider the wave propagating in the plane of particle rotation with an electric vector $iE\vec{x}_0 e^{i(\omega t - ky)}$ lying in the same plane. The motion in the wave field, which has a temporal dependence $e^{-ikr\sin\omega_B t}$ on the electron trajectory, leads to the appearance of harmonics of the cyclotron frequency in the force acting on the particle:

$$E_x = iEe^{i\omega t}\sum J_s(kr)e^{-is\omega_b t}, \quad (2)$$

where J_s is the Bessel function of the order *s*. Consequently, the resonance effect of the wave on the electron is possible on all cyclotron harmonics:

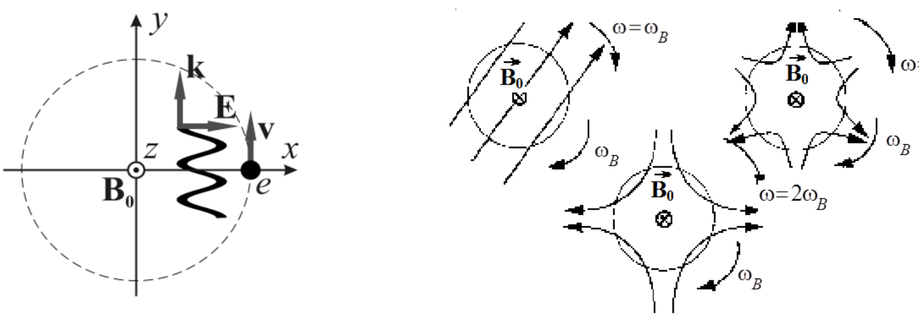
$$\omega = s\omega_B,\ s = 1, 2, \ldots . \quad (3)$$

The representation (2) corresponds to the expansion of the wave field on the particle trajectory over field multipoles (2*s*-poles). The harmonics *s* = 1, 2, 3, ... correspond to a rotating dipole, quadrupole, sextuple, etc. (Fig. 2b).

When the electron interacts with the transverse-electric TE_{mp} mode of the gyrotron cavity (Fig. 3), the mode field near the cavity axis coincides with the field of a single 2*m*-pole rotating with an angular frequency $\Omega = \omega / m$. In a LOG, where the particle rotates exactly around the cavity axis, the resonant interaction is only possible with a co-rotated wave and at a single cyclotron harmonic for which the strong rule of selection

$$s = m \quad (4)$$

is fulfilled. Due to the proximity of the structures of the mode and the resonant multipole the maximum possible coupling is achieved just in this case.



a) b)

Fig. 2. The wave field on the trajectory of a particle that rotates with a cyclotron frequency (a) can be represented as a set of rotating field multipoles *s* = 1, 2, 3 ... (b); one of co-rotating multi-poles can be in resonance with the wave.

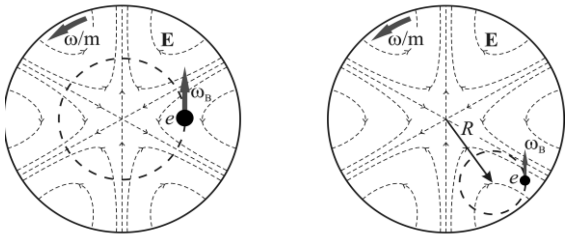


Fig. 3. The field of a TE_{mp} mode near the cavity axis coincides with the field of a rotating field 2*m*-pole for an electron rotating around the cavity axis (a) or represents the set of all multipoles at the displaced electron rotation center (b); in the first case (LOG), radiation is possible only at *m*th harmonic, and in the second case (conventional gyrotron) it can be at any cyclotron harmonic.

If the axes of the electron trajectories are located relatively far from the cavity axis (Fig. 3b; hollow beam in a conventional gyrotron) the field of the TE_{mp} mode near the particle presents a whole set of co- and counter-rotating field multipoles. In this case, the electron can resonantly interact at the harmonic *s* with a mode having any azimuthal index *m* if the corresponding structural factor is different from zero for the given radius of the electron guiding centers (Fig. 3b).

At the Institute of Applied Physics (IAP), LOGs are being studied in parallel with conventional gyrotrons during more than 20 years to obtain higher frequencies at lower magnetic fields. First experiments were carried out at the high-current electron accelerators with moderately-relativistic electron beams with voltage of (300 – 400) kV and, correspondingly, the electron Lorentz-factor was equal to 1.6-1.8. In these experiments, LOGs selectively operating at harmonics *s*=2-5 and frequencies from 20 GHz up to 0.4 THz were demonstrated [4, 5]. The further progress was characterized by transition from accelerators to simpler conventional high-voltage modulators with a lower operating voltage (80-30) kV and, simultaneously, by advancement to higher frequencies up to 1 THz.

In all sub-relativistic LOGs, we use electron-optical systems with cusp guns and a very large beam compression for formation of axis-encircling beams with a small spread of parameters. In such a system, electrons first move from a narrow ring emitter along magnetic lines of a weak magnetic field, then get an initial transverse velocity in a region of sharp changing of direction of the field (cusp), and after that their transverse velocity increases many times in the adiabatically increasing guiding field.

An important problem for any types of high-harmonic gyrotrons operating at relatively low voltages is a weak electron-wave interaction. In this case, gyrotron starting and optimal currents rapidly increases with the harmonic number: $I \propto \beta_\perp^{-2s}$, where the normalized transverse electron velocity is sufficiently small: $\beta_\perp^2 << 1$. At the same time, the achievable electron currents in short-wavelength gyrotrons are limited due to space charge effects at formation of beams with a small position and velocity spread. These two factors result in the use of long cavities ensuring very high diffraction Q-factors for the operating near-cutoff modes and simultaneously leading to a great share of Ohmic losses in the conventional cavities.

In the 80-kV LOG (Fig. 4a) [6], a stable single-mode second- and third-harmonic generation with a power of 0.3–1.8 kW in microsecond pulses was obtained at four frequencies in the range of 0.55–1.00 THz at magnetic fields 10.5–14 T. A relatively low efficiency ~1% at the third harmonic was caused by great Ohmic losses in the cavity in a long (24 wavelengths) conventional gyrotron cavity. This LOG was used for scientific applications [10] and testing various prospective new versions of THz cavities [11, 12]. The latter is aimed to significantly enhance gyrotron efficiency by decreasing Ohmic losses, as well as to achieve the fourth-harmonic operation [].

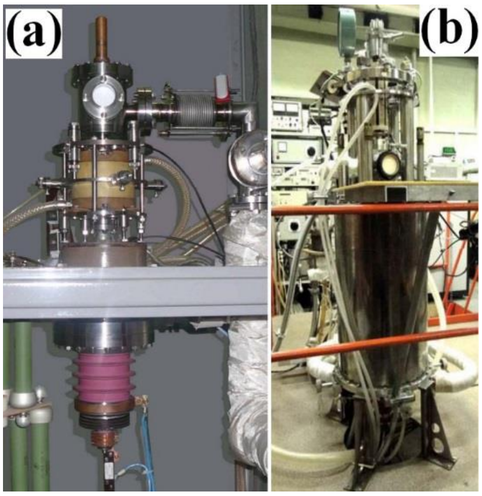


Fig. **4**. LOGs with parameters 1 THz/80 kV (a) and 0.394 THz /30 kV (b).

The next step in LOG development is creation of a 30 kV/0.7A gyrotron [13] with a 5 T cryomagnet designed for a CW operation (Fig. 4b). In this LOG, an axis-encircling electron beam with a large pitch-factor of 1.5 is formed in the cusp gun and in the adiabatically increasing magnetic field. The main scope of this setup is to provide operation at the second and third cyclotron harmonics at the frequencies of 0.26 THz and 0.39 THz, respectively, with the output power level of hundreds of Watts. The obtained experimental results are in a good accordance with theoretical simulations. Zones of excitation of the second-harmonic $TE_{2,5}$ mode and third-harmonic $TE_{3,7}$ mode are well separated by magnetic field. The second- and third-harmonic generation with parameters 800 W/ 0.267 THz and 300 W/ 0.394 THz is observed at B=5.02 T and B=4.93 T, respectively. At intermediate magnetic fields, competition of these two modes is observed.

An increase in operating magnetic field up to 6.3 T together with an increase in the accelerating electron voltage up to 45 keV should allow achieving frequencies up to 0.65 THz at the fourth cyclotron harmonic.

3. GYROTRINO FOR DNP-NMR SPECTROSCOPY

As was mentioned in Introduction, the integration of an NMR spectrometer and a compact low-voltage gyrotron in one cryomagnet (Fig. 5a) proposed in [7, 8] gives hope for the creation of a high-field DNP technique, available for many research laboratories. However, the integration leads also to specific problems that arise, firstly, because of the necessity of matching generation frequency with the DNP frequency, and secondly, due to the very limited room in the warm hole of the spectrometer cryomagnet and available region of the homogeneous magnetic field.

The gyrotron frequency ω is close to the relativistic cyclotron frequency of an electron, $\omega_B = \Omega/(1 + eU/mc^2)$, and to the electron paramagnetic resonance frequency, $\omega_{EPR} = (g/2)\Omega$. Here, $\Omega = eB/mc$ is the non-relativistic cyclotron frequency, U is the operating gyrotron voltage, $g = 2.0023$ is Landé factor. The relativistic cyclotron frequency is usually lower than the paramagnetic frequency in the same field B due to the electron Lorentz and Landé factors. To provide Dynamic Nuclear Polarization, the irradiation frequency ω should be equal to the EPR frequency (for Overhauser effect), or can be shifted by ratio of proton and electron spin resonance frequencies, 1/660 (for three-spin methods). Usually the operating voltage of (10-20) kV is used in medium-power gyrotrons for spectroscopy applications, so the relativistic cyclotron frequency is 2-4% lower than the EPR frequency. Such a frequency difference is difficult to eliminate by an additional warm coil wound around gyrotron without significant disturbing of the field homogeneity at the sample. The non-uniformity caused by a simple coil is about of 10^{-4} for typical parameters, whereas homogeneity better than 10^{-7} is desirable for NMR.

We proposed another possibility to provide the frequency matching, namely, use of an extremely low-voltage gyrotron (gyrotrino, Fig. 5) [7]. It simplifies the problem of NMR homogeneity since the magnetic field disturbance induced by the electron beam at the sample is about of 10^{-8} and can be neglected. For a low operating voltage, coincidence of gyrotron and EPR frequencies can be fulfilled because the gyrotron frequency is slightly higher than the cyclotron frequency. This excess, i.e. the frequency mismatch, $\Delta = \omega - \omega_c$, is needed for electron bunching in decelerating phase of microwave field in the gyrotron cavity. This mismatch depends on the length of gyrotron cavity L, and can be estimated as $L\Delta/v_z \sim 2\pi$, where v_z is the longitudinal electron velocity. Calculations show that at a very low operating voltage, namely 1-2 kV, and moderate cavity length, 10-20 λ (λ is the wavelength of terahertz radiation), frequency can be higher than the non-relativistic cyclotron frequency, and DNP conditions can be fulfilled [7].

When designing a gyrotrino, it is necessary to consider the effects, which are usually not very important for gyrotrons, in particular, the "hot" shift of the generation

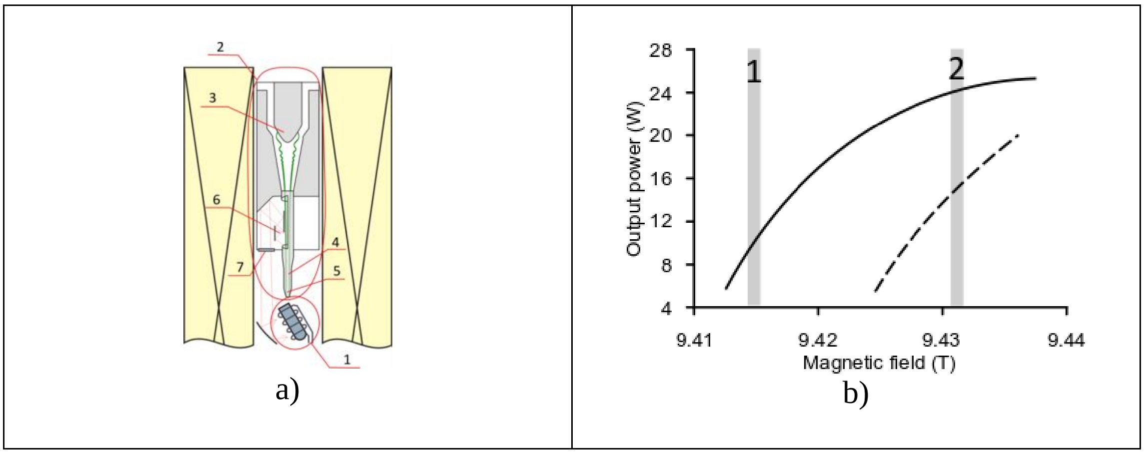


Fig. **5**. a) Gyrotrino in the cryomagnet of the NMR spectrometer (1 – a sample with an NMR sensor, 2 – gyrotrino, 3 - cathode, 4 - cavity, 5 – electron collector, 6 - quasi-optical mode converter, 7 - output window); b) calculated dependence of the output power for a 0.264-THz gyrotrino on the magnetic field for two sets of operating parameters: 1.5 kV / 200 mA (solid line) and 2 kV / 150 mA (dotted line). Shaded regions correspond to the regimes, in which the gyrotrino frequency coincides with the DNP frequencies for the Overhauser effect (1) and the solid effect (2).

frequency with respect to the mode frequency in the empty cavity that works in a favorable way. Calculations based on non-stationary equations with a non-fixed longitudinal structure of the microwave field in the cavity predict that a gyrotrino with an operating $TE_{6.2}$ mode, a voltage of 1.5 kV to 1.8 kV, a current of 200 mA and a pitch factor 1.2 can provide an output power up to 15 watts and efficiency 4% at the frequency of 0.264 THz with a required magnetic field of 9.42 T (Fig. 5b). The optimal parameters found in this way was then modeled with the PIC code CST Studio, based on a direct 3D simulation of the Maxwell equations and equations of particle motion. The results of two methods are in a good agreement.

To save space in the region of a homogeneous magnetic field, the gyrotrino cavity can be deployed in comparison with its usual arrangement by 180 degrees, then the radiation output will be directed toward the electron gun (opposite to the direction to the irradiated sample, Fig. 5a). The lack of space also leads to the impossibility of collecting electrons in a weak field region, however, the low power of the electron beam makes it possible to use a cavity cut-off narrowing located directly in a homogeneous high-intensity magnetic field as a collector of electrons.

At radiation output from the cathode end, a quasi-optical mode converter must be in front of the cavity. The calculations show that increasing the distance from the beam to the metal parts in the converter leads to decreasing the potential due to the space charge of the beam and formation of a virtual cathode, which in turn will lead to unstable operation of the electron gun. To reduce this effect, the converter design can be used, in which the beam transport channel does not break completely, but only the "visor" is cut out for it to output radiation, which makes the potential decrease insignificant. The developed quasi-optical converter consists of a concave (quasi-parabolic) mirror measuring 60 mm by 35 mm and two mirrors of complex shape located on one side of the transport channel. According to calculations based on integral equations, the conversion efficiency of the "gyrotrino" radiation into a Gaussian wave beam is 85%. After a barrier window, an additional mirror system will focus the radiation on the sample.

Although the ability to operate a gyrotron, which is a relativistic device by its operating principle, at low voltages is well known from theoretical calculations, in the previously published experiments the minimum working voltage of the gyrotron was 3.5 kV in the subterahertz range [14]; therefore, the possibility of operating at a very low voltage down to1.5-2 kV was verified in an existed CW second-harmonic 0.527 - THz gyrotron designed for operation in a cryomagnet with a field of up to 10 T at a voltage of 15 kV. According to calculations, the selected operating fundamental-harmonic $TE_{5,2}$ mode with the frequency 0.252 THz chosen for a special experiment should provide the output power 10-18 W at the voltage of 1.5-2 kV, current of 150 mA and pitch factor of about 1 [9].

The main difficulty in the experiment was the need to create an electron beam with a sufficiently high pitch factor at the extremely low voltage. When the voltage in the gyrotron magnetron-injection gun decreases, the initial transverse velocity of the particles in the near-cathode region, which is proportional to the ratio of the electric and magnetic fields at the cathode, decreases. Providing a pitch factor of about one at a low operating voltage was possible due to the use of a three-electrode magnetron-injection gun with the zero potential at the cavity and tube body, a negative operating voltage at the cathode, and a positive voltage at the anode. In this case, the pitch factor increased due to both an increase in the initial transverse particle velocity at the emitter and a decrease in the longitudinal velocity during electron deceleration between the anode and the cavity. In the experiment, the fundamental-harmonic generation at the given $TE_{5.2}$ mode with a frequency of 0.252 THz was observed at an operating voltage in the range from 15 to 1.5 kV [9]. The frequency was measured by a Fabry-Perot resonator. At voltages above 9 kV, generation was observed at the zero-anode potential. To maintain generation with lowering of the operating voltage it was needed to increase the anode potential. The electron current was maintained in the entire range of voltages at a level of 200 mA due to cathode heating. The measured dependences of the magnetic field and anode potential, at which the appearance of generation was observed (Fig. 7), corresponded to calculations with a good accuracy. At lowest voltages the calculated power of generation ~1W was significantly lower than the sensitivity of the existing calorimeter. In the experiment, the generation in such conditions was restered by a detector located about 2 m from the gyrotron, where a small part of the radiation was received. At low operating voltages (below 3 kV), the magnitude of the output signal grew with the anode potential increase, qualitatively corresponding to the calculated dependence of the output power on the pitch factor. At a voltage of 2 kV, increasing the anode potential above 3.1 kV resulted in a modulation of the output signal, which was apparently caused by the appearance of reflected electrons with an increase in the pitch factor. Thus, the possibility of an operation at a very low voltage down to 1.5 kV, required for integrating a gyrotron and an NMR spectrometer in one cryomagnet, was demonstrated for the first time in the experiment.

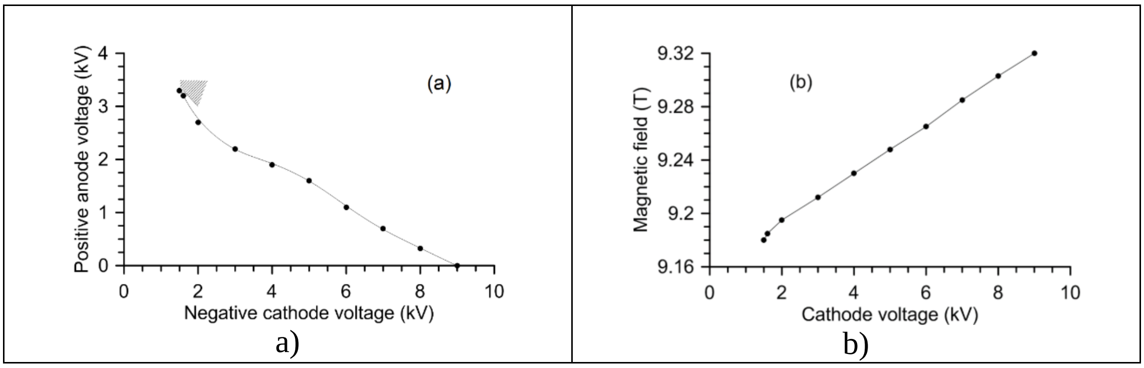


Fig. **6**. Measured dependences of voltage on the first anode (a) and magnetic field (b) on the accelerating voltage in the regime of occurrence of gyrotron generation; shaded area corresponds to modulation of signal due to reflection of electrons.

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