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# High-power terahertz sources for spectroscopy and material diagnostics

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## Contents



**Abstract. We review the development of radiation sources and present the most notable examples of the use of gyrotrons in spectroscopy and material diagnostics. We describe the main features of terahertz gyrotrons, present the most prominent examples of modern continuous-wave and pulsed gyrotrons for a specified frequency range, examine a number of topical applications, and discuss near-term development prospects for high-frequency gyrotrons.**

**Keywords:** gyrotron, terahertz radiation, power, spectroscopy

## 1. Introduction

The terahertz frequency range (0.1–10 THz) offers a number of specific features that make it very interesting for fundamental and applied research in the fields of physics, chemistry, biology, and medicine. Among the promising applications of terahertz waves are diagnostics and spectroscopy of various media, including electron paramagnetic resonance (EPR) and nuclear magnetic resonance (NMR) methods with high resolution [1, 2]. Strong terahertz radiation can be used to create dense plasma and control its parameters (controlled thermonuclear fusion, 'point-like' plasma sources of X-ray radiation, remote detection of ionizing radiation sources) [2], as well as for a number of technological and medical applications (see, e.g., [3]). The development of high-power radiation sources for this frequency range is difficult due to fundamental physical limitations: conventional vacuum tube devices (klystrons, backward or traveling wave oscillators) consist of elements with dimensions that are close to the wavelength, which leads to overheating or breakdown at high powers, while lasers have a low efficiency in the specified region. Although the power of vacuum tube devices significantly exceeds that of solid-state oscillators [4, 5] (the typical output power of backward wave oscillators [6] at a frequency of around 1 THz does not exceed 10 mW, while the power of klystrons with distributed interaction [7] reaches 100 mW), it is still insufficient for a number of modern applications. A natural solution to these problems is the transition to vacuum tube devices without retardation systems (i.e., operating with 'fast' waves), namely, to free-electron lasers (FELs) and gyrotrons.

With all their indubitable advantages — the ability to continuously tune the frequency in a broad range and high peak and average powers of radiation [8] — FELs are unique, large, and expensive devices, which are not available to many researchers. Therefore, one of the most promising devices for the terahertz (and subterahertz) frequency range are gyrotrons — devices based on the interaction of electrons rotating in an external magnetic field with the electromagnetic wave under the condition of cyclotron resonance [9]. The main distinction of a gyrotron from other cyclotron resonance masers (CRMs) is the use of an adiabatic magnetron injection gun (MIG) with electron-beam compression and an open highly selective cavity with diffraction energy output. Gyrotrons are much more compact than FELs and can operate at relatively small accelerating voltages, usually about several tens of kilovolts.

The state of the art in the field of THz gyrotron research is reviewed in detail in a number of publications (see, e.g., [3, 10–12]), and this article is an attempt to bring together all data on the development of radiation sources and to give the most interesting examples of the gyrotron use in experiments on the spectroscopy and diagnostics of various media. The article is structured as follows: Section 2 describes the main features of

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THz gyrotrons, Section 3 presents the most brilliant examples of modern continuous-wave (CW) and pulsed gyrotrons in the specified frequency region, Section 4 refers to actual applications, and in the conclusion we analyze the near-term prospects in the field of high-frequency gyrotron development.

## 2. Features of gyrotrons in the terahertz frequency range

The radiation mechanism of CRMs has been described in many papers (see, e.g., [13–15]). A general schematic of a gyrotron is shown in Fig. 1. This device has the following main subsystems: an electron-optical system, which forms the rotating electron beam with a high rotational energy and small velocity spread; an electro-dynamical system, in which the beam interacts with an eigenmode; an electron beam collector; an output system, which includes a consistent output window; and, in many cases, a quasi-optical converter, which transforms the operating mode into a paraxial wave beam [16]. An important element is the magnetic system (cryomagnets or pulsed magnets are typically used in the subterahertz and terahertz ranges), which creates an axially symmetric magnetic field that is needed for the formation of the electron beam and for the resonant interaction of electrons with the high-frequency field.

In a gyrotron, the rotational energy of electrons in the high magnetic field is transformed into high-frequency (HF) radiation. Under the condition of cyclotron resonance, the frequency of this radiation can be expressed as $\omega \approx n\omega_{\rm H} + hv_{\parallel}$, where $\omega_{\rm H}$ is the cyclotron frequency or gyrofrequency, which is proportional to the magnetic field, $v_{\parallel}$ is the electron drift speed, $n$ is the cyclotron harmonic number, and $h$ is the longitudinal wave number. The electron beam interacts with one of the eigenmodes of the round waveguide $\mathrm{TE}_{m,p}$ near the cutoff frequency ($h \approx 0$). Because the electron beam interacts with the fast wave, which propagates almost across the translational motion of electrons, there is no need for small-scale elements in retardation systems (such elements are essential for classic vacuum tube devices), and the device becomes weakly sensitive to the electron velocity spread.

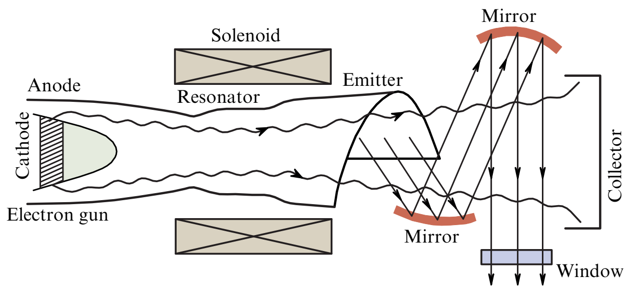


**Figure 1.** General schematic of a gyrotron with a built-in quasi-optical converter and radial power output.

We note that as the operational frequency increases, almost all quantities that determine the gyrotron power and efficiency [13, 15] decrease, and considerable effort is needed to maintain the gyrotron characteristics at the reasonable level. After many years of research, together with construction and technological developments, gyrotrons have reached high efficiency levels (up to 70% in systems with one-stage recuperation of residual electron energy [16–18] and power (2 MW at a frequency of 0.17 THz [19, 20], 200 kW at 0.67 THz [2, 21], and 5 kW at 1 THz [22]). Figure 2 is based on

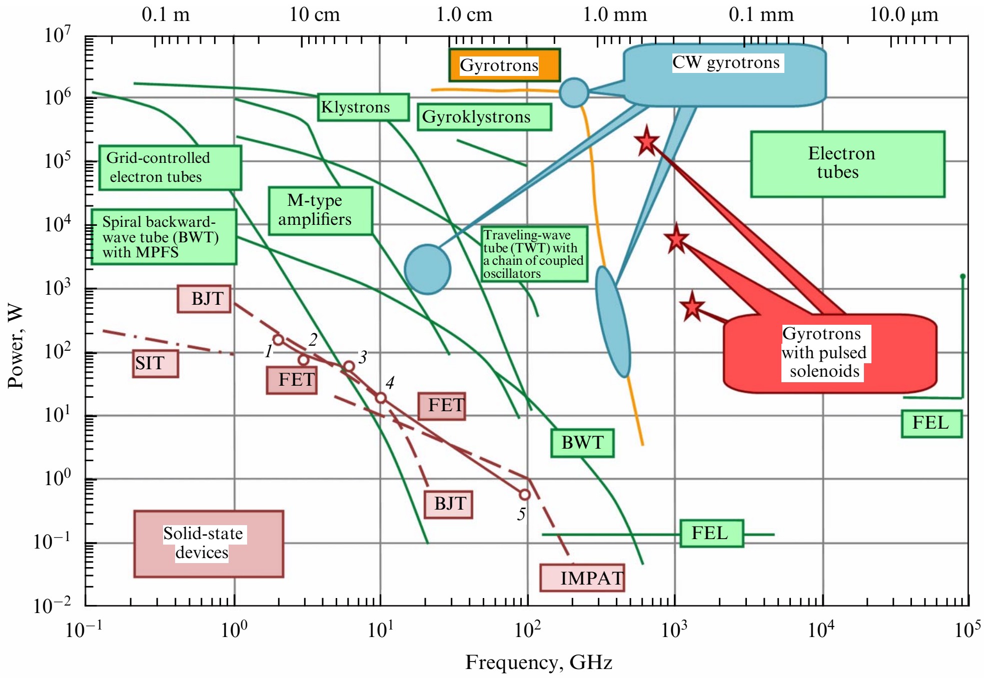


**Figure 2.** Power output levels achieved in electron devices (based on [23].) IMPAT — devices based on impact ionization avalanche transit-time diodes, BJT — devices based on bipolar junction transistors, FET — devices based on field effect transistors, SIT — devices based on static induction transistors, MPFS — magnetic periodic focusing system; *1* — devices based on Schottky-gate field effect transistors (MESFET) in GaAs (manufactured by Fujitsu, Japan), *2* — devices based on MESFETs in SiC (manufactured by Cree, USA), *3* — devices based on MESFETs in GaAs (manufactured by Toshiba, Japan), *4* — devices based on pseudomorphic high electron mobility transistors (PHEMTs) in GaAs (manufactured by Raytheon, USA), *5* — devices based on PHEMTs (manufactured by TRW, USA).

the data presented in [23] and shows power levels achieved in various electron devices.

Improvements in gyrotron operation in the sub-millimeter and terahertz ranges are connected with achievements in creating significantly strong magnetic fields and with the development of methods for operating mode selection in regimes with cyclotron resonance at higher-order harmonics. Reaching a relatively high power and efficiency in this range is a task facing fundamental and technological difficulties. The first ones are due to the decrease in the limit current of the electron beam formed by a MIG and by the increase in ohmic losses in the resonator walls. The second ones are associated with higher requirements for the actual device according to its calculated model, which include accuracy in manufacturing, relative positioning and adjustment of electron-optical and electrodynamic system elements in the magnetic field, resonator surface treatment, and the cooling system efficiency.

These technological problems have several solutions. First, it is desirable to operate at higher-order modes in order to increase the transverse dimensions of the resonator. An inevitable result of this increase is the growing importance of the problem of operating and parasitic mode competition due to the eigenmode spectrum crowding. To solve this problem, new dedicated methods for electron or electrodynamic selection are often needed. Without giving a detailed description of these methods in this review, we only note that electron selection is performed by choosing the radius of the electron beam (or several electron beams) to be such that the electron coupling to the operating mode field has the largest impedance, while the coupling to the parasitic modes is weak. Currently, this is achieved most efficiently in the so-called large-orbit gyrotrons, which use paraxial beams that effectively couple only to the modes that have the same azimuthal index as the cyclotron harmonic number [24]. Electrodynamic selection is usually performed in resonators with complicated profiles (for example, step-like, where the selection is performed by the effective coupling of two different eigenmodes in adjacent sections) [25].

Operating fields of 35 T and stronger, which are needed for the generation of a 1 THz frequency and higher under the conditions of fundamental cyclotron resonance ($n = 1$), can be quite easily realized in pulsed solenoids. Experiments with gyrotrons that operate in pulsed magnetic fields have shown that in developing gyrotrons with pulsed solenoids, a large number of specific requirements must be taken into account. These requirements should ensure the high mechanical strength of the construction and repeatability of the field amplitude from pulse to pulse. At the same time, the resonator conductivity should be, on the one hand, sufficiently low in order to decrease the pulsed magnetic field skinning (this is also the reason for the resonator to have thin walls) and, on the other hand, sufficiently high for the resonator ohmic $Q$-factor to significantly exceed its diffractive $Q$-factor and the gyrotron to not loose its efficiency.

For a long period of time, the only magnetic system type used in gyrodevices was cryomagnets based on coils from niobium–titanium cable (rarely adding a niobium–tin cable), dipped in liquid helium in order to provide the required operating temperature. The disadvantages of the specified systems include the necessity of long and costly procedures to maintain the liquid helium amount in the cryostat. At present, cryomagnetic systems with a built-in closed cycle cooler are gaining popularity. These systems do not require using cryogenic liquids and are called ‘dry’ cryomagnets. Many foreign companies industrially fabricate such magnetic systems, for example, JASTEC (Japan Superconducting Technology) (Japan), Sumitomo (Japan), Cryomagnetics (USA), and Oxford Instruments (England). For ‘dry’ cryomagnets with a maximal achieved field of 13–15 T, the lead aperture diameter does not exceed 110 mm [26], which limits the frequency at the level of 350–420 GHz for gyrotron operation at the first harmonic ($n = 1$) and the power, according to estimates, at about 300 kW. We note the development of a Russian dry cryomagnet model in 2015, which creates fields up to 10 T and has an 80 mm lead aperture. This magnet was developed and manufactured by the Cryomagnetic Department of the Lebedev Physical Institute, Russian Academy of Sciences (LPI RAS) in collaboration with the company RTI Cryomagnetic Systems, and it meets world standards, which gives hope that this field of research in science and technology will successfully develop in Russia in the nearest future.

Currently, magnetic fields in the range 35–40 T can be realized in ‘hybrid’ magnetic systems that consist of a water cooled solenoid and a cryomagnet. Such magnets are used, for example, in strong-magnetic-field laboratories in Europe (Grenoble) and the USA (Tallahassee), but these systems have a relatively small lead aperture diameter (around 50 mm), large dimensions (magnet length is about 3 m), and huge energy consumption (20 MW) [27]. For these reasons, such systems are not advantageous for application to gyrodevice development.

Pulsed solenoids are more likely to be used in experiments where pulsed generation is appropriate. In the late 2000s, two laboratories in Dresden and Los Alamos almost simultaneously achieved record high values of the pulsed magnetic field, 97 T [28]. Relatively compact solenoids with nitrogen cooling were developed at the Institute of Applied Physics, RAS (IAP RAS) [29]. These solenoids can produce fields of about 50 T in a volume that is large enough to fit an electrodynamic system of high-frequency gyrotrons with a pulse repetition rate of 1 every several minutes.

For a long time, the main goal of developers and gyrotron researchers was to increase the radiation frequency, efficiency, power, and pulse length. The development of new applications gave rise to new tasks: achieving high stability of frequency and power, broadening the range for continuous frequency tuning, increasing the device service life, and securing simple and comfortable conditions for operating personnel during the use of gyrotron systems.

In what follows, we briefly review modern achievements in terahertz gyrotron development and give the most interesting examples of applied research performed using high-power sources of terahertz radiation.

## 3. Examples of terahertz gyrotron realizations

The optimization of high-frequency gyrotrons is mostly performed by choosing parameters of the electrodynamic system and electron beam such that the efficiency is maximal and parasitic mode selection is achieved, especially in gyrotrons that operate at gyrofrequency harmonics.

At present, such research is mostly performed in the following organizations: Research Center for Development of the Far-Infrared Region, University of Fukui (FIR-FU) (Fukui, Japan) [30, 31], Massachusetts Institute of Technology (MIT) (USA) [32, 33], University of Maryland (UMD)

(USA) [34], Calabasas Creek Research Inc. (CCR) (USA) [35], Terahertz Research Center (THz RC) (Chengdu, China) [36], École Polytechnique Fédérale de Lausanne (EPFL) [38], and a subdivision of the Bruker Biospin company (in collaboration with Communications & Power Industries (CPI) company [39]). These companies are mainly developing gyrotrons and gyrotron systems for high-resolution spectroscopy.

A number of relatively low-power (several tens of watts) subterahertz gyrotrons have been developed at MIT, including gyrotrons on gyrofrequency harmonics. Relatively continuous frequency tuning in the 1 GHz bandwidth was achieved in a gyrotron with the 0.46 THz generation frequency [40]. The operation was shown to be stable for 21 days [41] and the ability to generate at low operating voltages (down to 3.5 kV) was demonstrated for the frequency of 0.233 THz [42].

CPI and Bruker Biospin companies (USA) perform short-run developments of subterahertz gyrotrons. A commercially available model of a high-resolution NMR spectrometer with dynamic nuclear polarization (DNP) was realized using a gyrotron with the generation frequency 0.26 THz [39]. Later, similar spectrometers were developed with DNP systems at 395 and 527 GHz. For these spectrometers, the Bruker–CPI company has developed and started mass production of gyrotrons with a power of around 50 W and frequencies of 263 GHz, 395 GHz, and 527 GHz, which are used in the Bruker company NMR/DNP systems with frequencies of 400, 600, and 800 MHz.

At the Research Center for the Development of the Far-Infrared Region (FIR-FU), a number of CW gyrotrons with axial outcoupling have been developed, including a gyrotron operating at 0.89 THz under the condition of synchronism with the cyclotron-frequency third harmonic and gyrotrons on the first and second harmonics in the range 0.2–0.4 THz with a built-in quasi-optical converter [43]. These impressive results are achieved mostly due to the use of unique cryomagnets that can create magnetic fields up to 20 T.

Recently, a CW gyrotron with the frequency 0.26 THz operating at the gyrofrequency first harmonic with a 'dry' cryomagnet and maximal power of 200 W was developed at the Center for Research in Plasma Physics at EPFL. Experimental results obtained with this gyrotron have shown good agreement with the calculated data, including complicated nonstationary generation regimes [38].

Regarding gyrotrons developed at the IAP RAS, we note that the fist experiments on the generation of sub-millimeter radiation were performed by institute fellows in 1970–1980 [44, 45]. All those gyrotrons were built using the simplest scheme with outcoupling of radiation in the operating mode. After the first success, the intensity of work in this field decreased, because the main task at that moment was the creation of megawatt gyrotrons for electron–cyclotron plasma heating and current control in systems for controlled thermonuclear fusion (CTF). In the early 2000s, a new start was given to investigations of THz gyrotrons due to the increasing number of prospective applications, including high-resolution spectroscopy. In 2009, a gyrotron for NMR/DNP spectroscopy was developed at the IAP RAS in collaboration with Scientific Production Enterprise (SPE) Gycom. It operates at the second harmonic of the gyrofrequency with a generation frequency of 0.258 THz and power up to 200 W. Frequency and generation power stabilities during 12-hour operation are no less than $3 \times 10^{-6}$ and $10^{-2}$, respectively [46]. Experiments using this oscillator at the Goethe University Institute of Biophysical Chemistry (Frankfurt, Germany) allowed increasing the sensitivity and resolution of the NMR spectrometer by a factor of 80 [47]. Among the disadvantages of the specified system, we note the liquid helium cryomagnet, which requires the addition of liquid helium once every several days, the insufficiently high efficiency of the external quasi-optical converter, and the absence of an automated control system, making it less attractive to consumers.

To avoid the specified disadvantages and improve operation of this kind of system, a new gyrotron system was designed. It was based on a 'dry' JMTD 10 T cryomagnet (not requiring liquid helium refilling) with a lead aperture diameter of 100 mm manufactured by the SASTEC company (Japan) [48–50]. Optimization of angles and design resulted in an assembly of a gyrotron for an automated system with a 0.263 THz frequency operating at the first harmonic of the gyrofrequency. Figure 3 shows the general view of this system, the control system interface, and the output power dependence on the magnetic field. The output power in the $TE_{53}$ operating mode, converted into a Gaussian beam inside the tube, reached 1 kW (with a 17% efficiency), which is more than enough for all planned applications of this system. The Gaussian component fraction in the output radiation of the gyrotron was 93% [50]. The generation frequency can be tuned in a small range by changing the magnetic field, the accelerating voltage, and the resonator temperature, which was successfully used during spectroscopy experiments with this system [51].

Russian and American developers independently suggested an interesting solution to significantly simplify the gyrotron system [52, 53]. The idea was to use the magnetic system of an NMR spectrometer as a magnet for the gyrotron as well. Such a gyrotron model was called 'gyrotrino'. This constructive solution allows the system to be very compact, simplifies the transmission line, and decreases the losses. Of course, it is more difficult to optimize such combined systems, because the number of degrees of freedom becomes strongly limited. These systems are at the beginning of their development, and there are probably many challenges that researchers will face in the future.

The first successful experiments with gyrotrons based on pulsed solenoids were performed in the 1980s at the IAP RAS under the direction of G S Nusinovitch, A G Luchinin, and M M Ofitserov (see [54]). These experiments used the fundamental cyclotron resonance and resulted in frequencies up to 0.65 THz, generation powers up to 40 kW, and an efficiency of several percent. In 2006–2007, mostly due to the collaboration between the IAP RAS and FIR FU, gyrotrons overcame the 1 THz level [55]. A Japanese version of the solenoid involved an original cooling system with liquid nitrogen, where additional structural strength was achieved by freezing wet powder that filled the solenoid volume. The solenoid itself was realized using a conventional scheme with lead aperture, which resulted in large energy consumption (300 kJ) and an extremely low pulse repetition rate (one pulse every 20 minutes). However, in these experiments at a frequency of 1 THz, which corresponds to the second harmonic of the gyrofrequency ($n = 2$), a power of several tens of watts was demonstrated for a pulse length of 1 ms. Almost simultaneously, another gyrotron was developed at the IAP RAS (Fig. 4). It was based on a pulsed magnet and had a number of constructive features, namely:

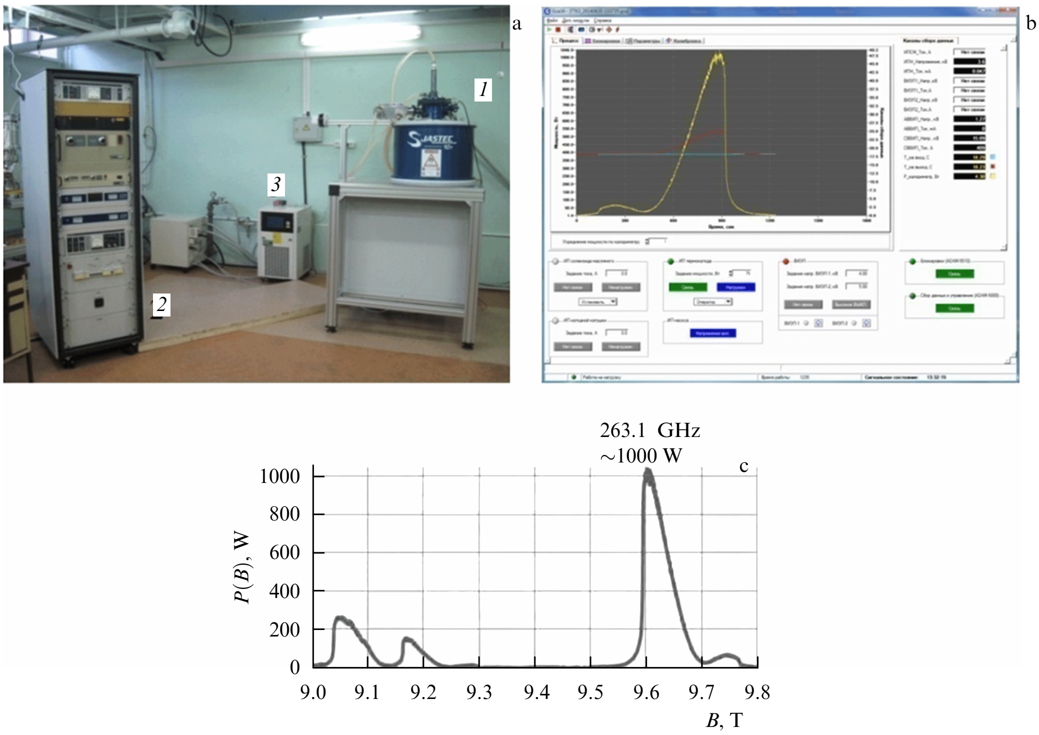


**Figure 3.** (a) Photograph of an automatic spectroscopy system based on a 0.26 THz/1 kW/CW gyrotron ($n = 1$) (IAP RAS–SPE Gycom): *1* — gyrotron in ‘dry’ cryomagnet, *2* — post with power supply and system of control, data acquisition, and safety interlockings, *3* — cooler–compressor that stabilizes the temperature of the liquid in the resonator cooling circuit. (b) Dialog window of the system software. (c) Output power versus the magnetic field.

— to achieve maximal energetic efficiency (decrease the magnetic field volume), the conducting lead of the solenoid was wound directly onto the gyrotron housing;

— to increase the mechanical strength of the construction, the winding was made from a composite cable. A central core made of an Nb–60% Ti alloy mechanically reinforces the outer lead shell of the cable;

— to decrease ohmic losses, increase mechanical strength, and improve thermal stability, liquid nitrogen was used as a passive coolant. Using liquid nitrogen allowed decreasing the ohmic resistance of the solenoid by a factor of seven compared to the value measured at room temperature;

— the dimensions of the solenoid with a rectangular cross section were designed in order to optimize the longitudinal distribution of the magnetic field, which was calculated numerically.

The solenoid was powered by a specially developed power source with a capacitor bank as an energy storage unit with an energy up to 5.6 kJ (maximal voltage 3.5 kV, maximal current 6 kA). A stabilization scheme provided 99.95% repeatability of the magnetic field amplitude, which allowed maintaining gyrotron operation in the single-pulse regime and with optimal efficiency over many pulses. During testing, the solenoid produced several thousand pulses, which did not affect its characteristics. The pulse repetition rate was limited by the time needed for the solenoid to cool to the liquid nitrogen temperature and amounted to one ‘shot’ per minute. Terahertz radiation was detected using a point-contact diode and a calorimeter with a sensitivity of around 10 mJ in one pulse. As the magnetic field (solenoid current) was changed, a sequence of modes was observed with frequencies close to 1 THz and power up to 5 kW. The $TE_{17.4}$ mode with a frequency of 1.022 THz, radiation energy of 100 mJ, and pulse length of 20 μs was excited at the magnetic field 38.5 T and the electron beam parameters equal to 24 kV and 3 A (Fig. 4c) [56]. A relatively small generation efficiency (2–3%) is mainly caused by the large resonator length, which was made two times larger than the optimal one in order to reliably excite the operating mode. A heterodyne system was used to measure the frequency of single pulses; the signal from the gyrotron was mixed with the harmonic of the reference microwave synthesizer. The measured frequency (1.022 THz) is close to the cyclotron resonance frequency (1.024 THz), which is calculated using the value of the magnetic field. Further increasing the solenoid current in the same device resulted in a record high value of the gyrotron generation frequency: 1.3 THz with 1.5 kW power [22].

The next project involving a pulsed solenoid was a high-power gyrotron (Fig. 5) for the initiation of a point gas discharge. It was developed in the well-known $TE_{31.8}$ operating mode, which was successfully used in experiments on CTF application, and produced single pulses with a duration of 20–30 μs, a power of 200 kW, and a frequency of 0.7 THz [21, 57].

The question of whether it is possible to increase the pulse repetition rate in such systems remains open. The theoretical analysis presented in [58] shows that in principle it is possible to reach a pulse repetition rate of 2 Hz for a 40 T magnetic field. The authors suggest a construction with an improved heat removal from the solenoid achieved by spatially separated edges and the solenoid winding made of a foil conductor. Unfortunately, first experiments on realizing this construction ended with solenoid destruction at fields that were approximately two times smaller than the nominal value. Nevertheless, there are ongoing projects on the development of solenoids with coolant pumping through the windings, which should in theory result in an increased pulse repetition rate.

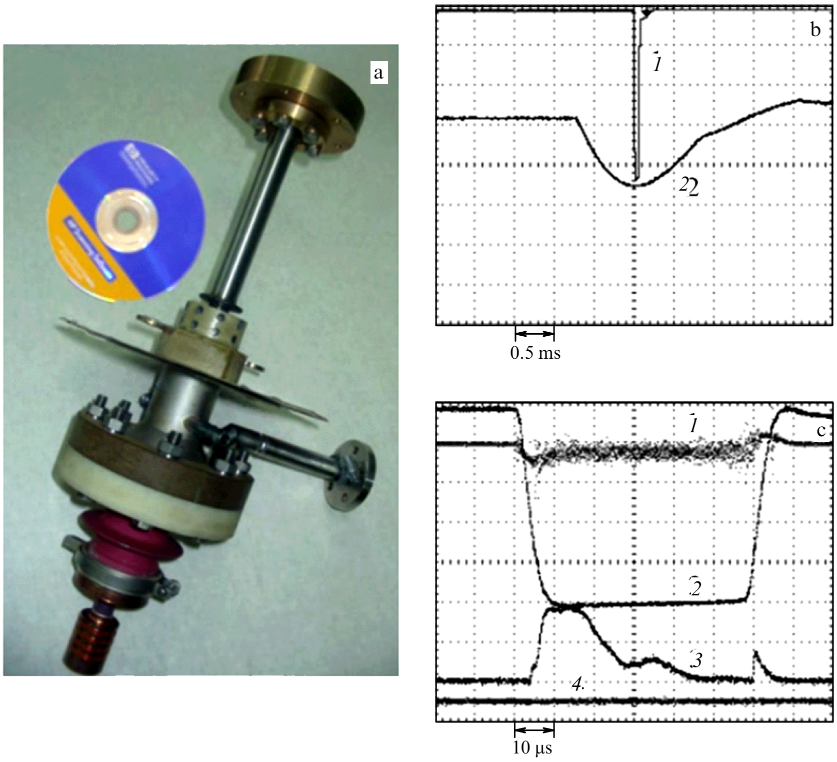


**Figure 4.** (a) Terahertz gyrotron with a pulsed solenoid. (b) Signal on the oscilloscope screen: *1* — gyrotron cathode voltage, *2* — solenoid current (magnetic field). (c) Similar dependences on a scale that is twice as large: *1* and *2* — current and voltage of the electron beam, *3* — microwave power (detector signal), *4* — solenoid current (magnetic field).

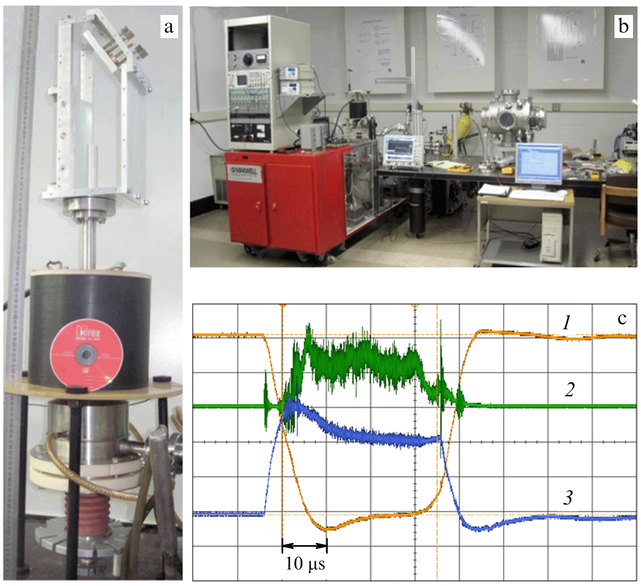


**Figure 5.** (a) High-power gyrotron with a pulsed solenoid and a quasi-optical converter. (b) Experimental workbench [21]. (c) Signal visualization on the oscilloscope screen: *1* — accelerating voltage, *2* — electron beam current, *3* — microwave power (detector signal).

We note a feature of gyrotrons with pulsed solenoids that is of undoubted practical interest. As the magnetic field is varied, a sequence of modes with close eigenvalues is excited in a quite broad frequency range (10–15%). Due to this effect, the generation frequency can be changed relatively easily from pulse to pulse by changing either the voltage on the energy storage device or the time delay between the gyrotron cathode high-voltage pulse and the solenoid current pulse (and, correspondingly, change the solenoid current at the moment of the high-voltage pulse). Moreover, a high-voltage pulse can be applied not at the top but at the front of the solenoid current pulse, which would result in the generation of a sequence of short pulses at different frequencies.

Operation at high harmonics of the cyclotron frequency is almost impossible in conventional gyrotrons due to the competition of these harmonics with low harmonics, unless effective mode selection methods are applied. Electrodynamic selection methods are based on using resonators with complicated profiles, in particular, coupled resonators with mode transformation [59, 60], where the selection is based on the excitation of a bunch with modes at the same frequency with the same azimuthal and close radial indexes. These methods are difficult to implement due to the requirement of micrometer accuracy during the fabrication of cylindrical resonators with a radius of 1.5–2.0 mm and length of several (in some particular cases up to ten) millimeters. Another discussed method involves using sectioned electron beams in one gyrodevice (multibeam gyrotrons) [61, 62]. In this case, an additional electron beam can be used either to improve the efficiency of the operating mode excitation (an active additional beam, with the fraction of electron rotational energy in this beam being quite high, approximately 0.6–0.7 times the total energy) or to absorb the energy of parasitic oscillations (in this case, the ratio of rotational energy at the beginning of the interaction volume is small). Currently, a new gyrotron is being developed with two generating beams. This gyrotron is planned to generate the 0.79 THz frequency with the power of 100 W by exciting the $TE_{8.5}$ operation mode at the second harmonic of the gyrofrequency [63].

V L Bratman's group obtained THz generation at the second and third harmonics of the gyrofrequency in a large-orbit gyrotron (LOG) at the IAP RAS. Generation at the second harmonic had the frequency 0.6 THz and the power up to 2 kW; at the third harmonic, the frequency was 1 THz and the power 0.3 kW, with a 10 μs pulse length; the magnetic field was around 15 T and the electron beam voltage was 80 kV [64]. The authors used a Bitter magnet with effective water cooling, which allowed a pulse repetition rate of 0.1 Hz to be achieved.

Successful realization of a LOG using a pulsed solenoid was a starting point for the development of a LOG in a cryomagnet. Such a system can possibly allow CW generation. The main reason for the LOG not being widely used is the difficulty of applying the electron-optical system (EOS) that forms the paraxial electron beams. Usually, such an EOS requires a magnetic system with a function of field reversal, which, on one hand, requires development of specific solenoids and, on the other hand, requires a high accuracy of longitudinal adjustment of a gyrotron in the magnetic field.

However, there are many reasons to be optimistic, because there are already a number of successful realizations of such systems. Besides the mentioned terahertz LOG, we note the LOG in a permanent magnet, on which it was possible to selectively excite a sequence of modes through the fifth harmonic [65]. A frequency of 0.15 THz was obtained at the fifth cyclotron harmonic and, although the experiment was performed in a pulsed regime, the gyrotron design (with corresponding power sources available) could in principle support CW operation.

## 4. Some applications of terahertz gyrotrons

We do not discuss the well-known 'classic' fields of gyrotron application, such as plasma heating and current control using CTF setups or gyrotron applications in microwave technologies (including for the synthesis of ceramic materials or growth of diamond films and discs using chemical vapor deposition). Instead, we try to give a short review of new applications that have arisen due to the development of terahertz gyrotrons and, in turn, have been the motivation for these developments.

Currently, spectroscopic applications are being developed most intensively, especially the high-resolution NMR/DNP spectroscopy (see, e.g., [66]). A microwave radiation source with a relatively high intensity can increase the signal-to-noise ratio by one to two orders of magnitude and, correspondingly, significantly shorten the time needed for data accumulation (Griffin in his report [67] gives an impressive estimate: from more than four years to one day). At the moment, there is a standard set of reference spectroscopic frequencies, which are multiples of frequencies used for NMR (200 MHz, 400 MHz, ... , 1200 MHz), the corresponding magnetic fields (from 9.4 T to 23.5 T), and the required radiation frequencies (from 0.26 THz to 0.79 THz). This determines the frequency that developers choose when designing THz CW gyrotrons.

The next interesting application is the use of THz radiation for biomedical purposes. A number of publications (see, e.g., [68]) describe the difference in absorption of healthy and malignant (cancer) cells (which is likely to be caused by the liquid content), which reaches a factor of 3–5 in the frequency range 0.3–0.5 THz. This demonstrates the ability to selectively act on affected regions. Examples of such local terahertz therapy are presented, for instance, in [69]. In experiments with rats, the size of cancer tumors steadily decreased to zero under the action of radiation from a 0.2 THz gyrotron. At the same time, in the control group, the tumor size increased by an order of magnitude every three weeks.

Another application is localized action on biological tissues located at relatively small depths below the human skin (comparable with the field penetration depth). In particular, in [69], the authors describe the action of radiation with 0.2–0.4 THz frequencies that stimulates the regeneration of human hair. Obviously, such methods need thorough testing, but appear to be very interesting.

Finally, speaking of long-pulse or CW gyrotrons, we mention 'teravision': sharp imaging in THz radiation, which can be used to detect different kinds of substances and can be applied to security check systems and visualization of objects and impurities that are invisible using conventional methods [70, 71]. With few exceptions, all specified applications need relatively low power, around several dozen or a maximum of several hundred watts.

Much higher power is needed for dense plasma diagnostics or the initiation of localized gas discharges. Using estimates for the signal-to-noise ratio and radiation powers that are achievable today, we can assume, for example, that in order to diagnose plasma in the LHD (Large Helical Device) stellarator (Japan) in the electron temperature range, which is the most interesting range for the plasma physics community, high-power gyrotrons with the frequencies 0.6–0.7 THz must be used. Currently, such gyrotrons are realized using pulsed magnets. Unfortunately, we have to admit that the radiation frequency of gyrotrons with pulsed magnets is not stable enough for spectroscopy and diagnostics applications. Therefore, there are projects to create gyrotrons in cryomagnets with relatively small powers (several hundred kilowatts) and frequencies of around 0.3 THz [72, 73].

High-power pulsed THz radiation can induce high electric fields in localized volumes, which can be used for the initiation of point gas discharge. For a natural ionization background, the probability of finding a free electron in such a volume is quite small and the discharge is therefore unlikely to happen. This means that by detecting a discharge after a sequence of pulses, an excess of the natural ionization background can be detected. Such an effect can be used for the detection of hidden radioactive sources from a distance of several dozen meters. A similar approach was suggested by Nusinovich and Granatstein [74] and was investigated in a joint project by the IAP RAS and the University of Maryland [75] using a high-power pulsed gyrotron at a frequency of 0.67 THz [21].

The same gyrotron with a 100 kW power of output radiation was successfully used at the IAP RAS for the initiation of point discharge in an inhomogeneous gas jet for a broad range of pressures. These experiments allowed the first realization of an intensive point-like radiation source in the UV range. The size of the emitting region is less than 1 mm and the radiation power in the wavelength range of 10–100 nm is up to 10 kW, integrated over the full solid angle [76]. Such a discharge can possibly be used in the future to create a point-like source of extreme UV radiation for nanolithography applications.

Among spectroscopy applications of gyrotrons, we mention one that is of great fundamental importance — the experimental spectroscopy of the lightest atom, positronium (see [77, 78]). In order to solve this problem, a new

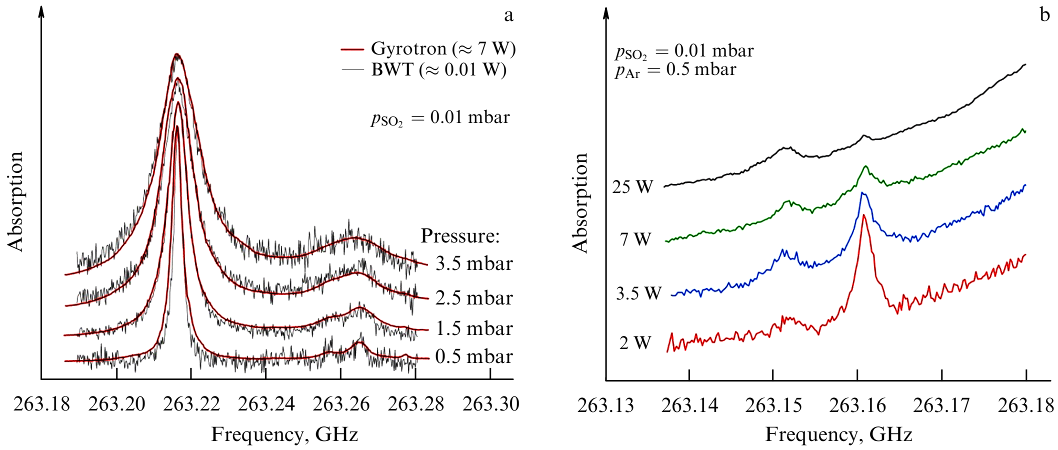


**Figure 6.** (Color online.) Examples of experimental spectra of a mixture of $SO_2$ and argon, obtained using a RAD spectrometer with a gyrotron at room temperature: (a) for different pressures of the gas in the chamber (indicated in the figure) and constant radiation power; (b) for different radiation powers (indicated in the figure) and constant pressure. The partial pressure $p_{SO_2}$ in the mixture is 0.01 mbar. For clarity, each spectrum has a constant vertical offset with respect to the previous one. Broken grey lines in figure (a) show spectra obtained using BWT radiation with a power of about 0.01 W and red smooth curves show spectra obtained using gyrotron radiation with a power of about 7 W. Constant time of synchronous detection is 1 s.

gyrotron was developed at FIR FU (Japan). This device has the capacity to use several resonators with slightly different dimensions. Due to the set of resonators and the possibility of varying the magnetic field, it was possible to almost continuously tune the frequency in the range 201–205 GHz [77]. Moreover, by changing the operating mode, the gyrotron frequency can be changed to approximately 180.6 GHz [78]. High-power coherent radiation should induce a magnetic dipole transition that corresponds to a change in the mutual orientation of electron and positron spins and is actually a transition from the positronium orthostate (total spin 1) to the parastate (total spin 0). The probability of this transition is very low. Due to the short positronium lifetime (the orthostate can exist in the vacuum for approximately 140 ns), observing such a transition requires high-power radiation (more than 20 kW) at a resonant frequency that currently can be produced only by gyrotrons. The measurements were performed at seven frequencies in the theoretically predicted spectrum range. The results showed absorbance with a signal-to-noise ratio of around 10, which corresponded to the positronium line. The signal was shown to be absent at a significant offset from the resonant frequency. The position of this line in the spectrum corresponds to the width of superfine splitting of the positronium atom in the ground 'electron' state and its width corresponds to the parapositronium decay time. These parameters were first obtained from direct spectroscopic measurements. The described investigations of a simple conventional quantum mechanical system like positronium are of great significance for the verification of quantum electrodynamics predictions.

To end this short review, we mention another field where the application of high-power gyrotron radiation appears to have potential: classical high-resolution molecular gas spectroscopy. This field of science is currently well developed, but there are still many fundamental and applied problems that can be solved by increasing the spectrometer sensitivity. At the same time, the sensitivity of many instruments that use classic spectroscopic methods in the millimeter–submillimeter wavelength range (analysis of radiation that passes through a gas or registration of a re-emitted electromagnetic field) has reached its limit set by fundamental physical principles. The only known method that can theoretically overcome this sensitivity limit is the optoacoustic detection of absorption. The absorption of radiation by gas results in heating, which, in turn, gives rise to an acoustic wave, which can be detected, for example, using a microphone. The output signal in this case is directly proportional to the absorbed power. The absorption sensitivity of this method increases as the radiation power increases. This principle is used in spectrometers with radio-acoustic detection (RAD) of absorption, which was developed and assembled at the IAP RAS and has been successfully used for several decades [79].

The first attempt to improve the RAD spectrometer sensitivity by using a gyrotron as a radiation source was made more than 40 years ago [80]. A tenfold increase in the output RAD signal was observed when the radiation power was correspondingly increased. However, the gyrotron that was used in the experiments in [80] did not allow continuously tuning the frequency; therefore, it was impossible to fully measure the spectra. Due to this problem, the interpretation of the obtained results is not reliable, because the measured spectra may contain parasitic signals that correspond to the radiation absorption in the gas cell elements, instead of the gas itself. Thus, experiments [80] were discontinued until recently.

The next step in this direction is connected with the development of a gyrotron system at the IAP RAS [50]. For the first time in the history of gyrotrons, the parameters of the system allowed obtaining continuous spectra typical for high-resolution molecular gas spectroscopy. The first experiments were performed with a mixture of sulfur oxide ($SO_2$) and a nonabsorbing 'buffer' gas, argon. Typical absorption spectra measured using a modern version of the RAD spectrometer [81] with a gyrotron system [50] are shown in Fig. 6 together with similar spectra obtained using backward wave tubes (BWTs), which are conventionally used in such spectrometers. After increasing the radiation power from several fractions of a watt to several watts, it became possible to observe the previously theoretically predicted transitions in the $SO_2$ molecule at the frequencies of 263.151 and 263.161 GHz (Fig. 6b). The spectrometer sensitivity to the absorption coefficient according to measurements with BWTs is about $5 \times 10^{-7}$ cm$^{-1}$ for a constant time of synchronous detection of 1 s. When using a gyrotron system with the radiation power around 7 W, the sensitivity reached the level of $6 \times 10^{-10}$ cm$^{-1}$.

To summarize, by analyzing the absorption spectra of known spectral lines, it was demonstrated for the first time that by increasing the radiation power by approximately three orders of magnitude, we can proportionally increase the RAD-spectrometer sensitivity. We note that the achieved sensitivity of the spectrometer is not the limit. While using a gyrotron, it is still possible to apply a conventional method for enhancing the RAD-spectrometer sensitivity by increasing the effective length of radiation–gas interaction. Such a method can result, as was shown previously [82, 83], in sensitivities to absorption of $10^{-9} - 10^{-11}$ cm$^{-1}$, when using BWTs. This gives hope that a record high sensitivity of around $10^{-13}$ cm$^{-1}$ can be achieved when simultaneously applying both methods. This could open colossal opportunities for applications in the field of quantitative and qualitative gas analysis.

The fundamental limitation for further increasing the sensitivity is not determined by the gyrotron radiation power, which could have been increased even in the first experiments. Instead, this limitation is associated with equalizing populations at the molecule rotational levels between which the transition occurs (so-called spectral line saturation and the associated self-induced transparency effect). Under the action of a resonant field, the level populations can equalize faster than the collisional relaxation of corresponding states occurs. This is why the $SO_2$ molecule, having a large dipole moment (approximately 1.6 D), is not the optimal object for achieving record-high sensitivity. Even when $SO_2$ is significantly diluted by a buffer gas, the influence of the saturation effect is quite high. This effect manifests itself when the radiation power is increased, as can well be seen, for example, in Fig. 6b from a change on the line profile near the frequency of 263.161 GHz. The influence of the effect can be minimized by choosing the transition type (with a smaller value of dipole moment matrix element) and by optimizing the observation conditions (line broadening by the buffer gas pressure).

## 5. Conclusions

The upper limit value of the operation frequency of gyrotrons is mainly determined by the abilities to create magnetic fields of several tens of T in volumes large enough to fit the electrodynamic system of gyrodevices in indestructible solenoids. This limitation can be partially removed by switching operation to gyrotron harmonics. But this last method involves high requirements to the operation mode selection. The problem is additionally complicated by mode competition and ohmic losses. Despite the mentioned difficulties, there are successful realizations of terahertz gyrotrons, which by power overcome all other radiation sources in this range. Based on heat loads on construction elements of megawatt-power gyrotrons, operating at a frequency of 0.17 THz, one can assume that similar heat loads (with the resonator superdimensionality remaining the same, i.e., using similar operation modes) should approximately correspond to powers of about 250–1000 kW and 10 kW at the respective frequencies of about 0.3 THz and 1 THz in the CW-generation regime.

To conclude, there are still many possibilities for improving gyrodevices, and in the nearest future it will be possible to increase the power and to reach operation frequencies up to 2 THz. The development of such relatively compact radiation sources will enable many applications where high-power THz radiation is needed.

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## References

1. Blank M, Rosay M, Engelke F *J. Magn. Reson.* **264** 88 (2016)
2. Glyavin M Yu et al. *Radiophys. Quantum Electron.* **54** 600 (2011); *Izv. Vyssh. Uchebn. Zaved. Radiofiz.* **54** 666 (2011)
3. Bratman V L et al. *J. Infrared Millim. Terahertz Waves* **33** 715 (2012)
4. Lewis R A *J. Phys. D* **47** 374001 (2014)
5. Siegel P H *IEEE Trans. Microw. Theory Tech.* **50** 910 (2002)
6. Negirev A A, in *Vakuumnaya SVCh Elektronika* (Vacuum Microwave Electronics) (Ed. M I Petelin) (Nizhny Novgorod: IAP RAN, 2002) p. 93
7. Communications & Power Industries (date of the application: 21.03. 2016), http://www.cpii.com/product.cfm/7/40/?218
8. Vinokurov N A, Kulipanov G N, Skrinskii A N *Herald Russ. Acad. Sci.* **81** 229 (2011); *Vestn. Ross. Akad. Nauk* **81** 6 520 (2011)
9. Gaponov A V, Petelin M I, Yulpatov V K *Radiophys. Quantum Electron.* **10** 794 (1967); *Izv. Vyssh. Uchebn. Zaved. Radiofiz.* **10** 1414 (1967)
10. Bratman V et al. *IEEE Trans. Plasma Sci.* **37** 36 (2009)
11. Glyavin M Yu et al. *Radiophys. Quantum Electron.* **52** 500 (2009); *Izv. Vyssh. Uchebn. Zaved. Radiofiz.* **52** 557 (2009)
12. Manuilov V et al. *J. Infrared Millim. Terahertz Waves* **31** 912 (2010)
13. Nusinovich G S *Introduction to the Physics of Gyrotrons* (Baltimore: The Johns Hopkins Univ. Press, 2004)
14. Kartikeyan M V, Borie E, Thumm M K A *Gyrotrons. High Power Microwave and Millimeter Wave Technology* (Berlin: Springer, 2004)
15. Tsimring Sh E *Electron Beams and Microwave Vacuum Electronics* (Hoboken, NJ: Wiley-Intersci., 2007)
16. Denisov G G et al. *Radiophys. Quantum Electron.* **46** 757 (2003); *Izv. Vyssh. Uchebn. Zaved. Radiofiz.* **46** 845 (2003)
17. Glyavin M Yu et al. *Int. J. Infrared Millimeter Waves* **18** 2129 (1997)
18. Sakamoto K et al. *Phys. Rev. Lett.* **73** 3532 (1994)
19. Tumm M "State-of-the-art of high power gyro-devices and free electron masers", KIT Scientific Reports 7662 (Karlruhe: Karlsruher Institut für Technologie, 2013)
20. Litvak A G et al., in *Proc. of 8th Intern. Workshop "Strong Microwaves and Terahertz Waves: Sources and Applications", Nizhny Novgorod, Russia, July 9–16, 2011*, p. 13
21. Glyavin M Yu et al. *Appl. Phys. Lett.* **101** 153503 (2012)
22. Glyavin M Yu, Luchinin A G *Int. J. Terahertz Sci. Technol.* **2** 150 (2009)
23. Temkin R, in *Proc. of the 39th Intern. Conf. on Infrared, Millimeter and Terahertz Waves, IRMMW-THz, Tucson, AZ, USA, September 14–19, 2014* (Piscataway, NJ: IEEE, 2014) p. 1
24. Bratman V L, Kalynov Yu K, Fedotov A É *Tech. Phys.* **43** 1219 (1998); *Zh. Tekh. Fiz.* **68** (10) 91 (1998)
25. Pavel'ev V G, Tsimring Sh E "Otkrytyi rezonator" ("Jpen resonator"), Author's Certificate No. 661664, priority of 15.08.1977; *Ofitsial'nyi Byull. Komiteta Po Delam Izobretenii Otkrytii Soveta Ministrov SSSR* (17) 234 (1977)
26. JASTEC Japan Superconductor Technology, Inc.: Products, application date: 21.03.2016, http://www.jastec-inc.com/e_products_cryogen/index.html
27. Laboratoire National des Champs Magnétiques Intenses — Grenoble, application date: 20.03.2016, http://lncmi-g.grenoble.cnrs.fr/spip.php?rubrique105&lang=en
28. New and Emerging Technology News. 2012, application date: 20.03.2016, http://www.gizmag.com/100-tesla-pulsed-magnet/21946
29. Glyavin M Yu et al. *Instrum. Exp. Tech.* **54** 77 (2011); *Prib. Tekh. Eksp.* (1) 84 (2011)
30. Idehara T, Sabchevski S P *J. Infrared Millim. Terahertz Waves* **33** 667 (2012)

31. Idehara T et al. *Thin Solid Films* **517** 1503 (2008)
32. Torrezan A C et al. *IEEE Trans. Plasma Sci.* **38** 1150 (2010)
33. Jawla S et al., in *Proc. of the 36th Intern. Conf. on Infrared, Millimeter and Terahertz Waves, IRMMW-THz, Houston, TX, USA, 2 – 7 October 2011* (Piscataway, NJ: IEEE, 2011)
34. Dumbrajs O, Nusinovich G S *Phys. Plasmas* **19** 103112 (2012)
35. Read M et al., in *Proc. of the 8th IEEE Intern. Vacuum Electronics Conf. IVEC'07, Kitakyushu, Japan, May 15 – 17, 2007* (Piscataway, NJ: IEEE, 2007) p. 347
36. Yan Y et al. *Chin. J. Electron.* **22** (2) 415 (2013)
37. Alberti S et al. *Phys. Plasmas* **19** 123102 (2012)
38. Dynamic Nuclear Polarization. Terahertz Technology. Bridge12. 2016, application date: 21.03.2016, http://www.bridge12.com/
39. Blank M et al., in *Proc. of the 15th IEEE Intern. Vacuum Electronics Conf. IVEC 2014, Monterey, Calif., USA, April 22 – 24, 2014* (Piscataway, NJ: IEEE, 2014) p. 7
40. Hornstein M K et al. *IEEE Trans. Electron Devices* **52** 798 (2005)
41. Bajaj V S et al. *J. Magn. Reson.* **160** 85 (2003)
42. Hornstein M K et al. *IEEE Trans. Plasma Sci.* **35** 27 (2007)
43. Idehara T et al. *Vacuum* **62** 123 (2001)
44. Zaytsev N I et al. *Radio Eng. Electron Phys.* **19** 103 (1974)
45. Glyavin M Yu et al., in *Girotrony* (Gyrotrons) (Exec. Ed. V A Flyagin) (Gor'kii: IAP AN SSSR, 1989) p. 73
46. Venediktov N P et al. *Radiophys. Quantum Electron.* **53** 237 (2010); *Izv. Vyssh. Uchebn. Zaved. Radiofiz.* **53** 260 (2010)
47. Denysenkov V et al. *Phys. Chem. Chem. Phys.* **20** 5786 (2010)
48. Glyavin M Yu et al. *Radiophys. Quantum Electron.* **58** 639 (2015); *Izv. Vyssh. Uchebn. Zaved. Radiofiz.* **58** 709 (2015)
49. Glyavin M Yu et al. *Radiophys. Quantum Electron.* **58** 649 (2015); *Izv. Vyssh. Uchebn. Zaved. Radiofiz.* **58** 720 (2015)
50. Glyavin M Yu et al. *Rev. Sci. Instrum.* **86** 054705 (2015)
51. Chirkov A et al., in *Proc. of the 4th Russia–Japan–USA Symp. on Fundamental and Applied Problems of Terahertz Devices and Technologies, RJUS TeraTech-2015, June 9 – 12, 2015 IMT RAS, Chernogolovka, Russia* (2015)
52. Bratman V L et al. *Radiophys. Quantum Electron.* **56** 532 (2014); *Izv. Vyssh. Uchebn. Zaved. Radiofiz.* **56** 589 (2013)
53. Grantome: The entirety of funding information, application date: 20.03.2016, http://grantome.com/grant/NIH/R44-GM108179-03
54. Flyagin V, Luchinin A, Nusinovich G *Int. J. Infrared Millimeter Waves* **4** 629 (1983)
55. Idehara T et al. *Int. J. Infrared Millimeter Waves* **27** 319 (2006)
56. Glyavin M Yu, Luchinin A G, Golubiatnikov G Yu *Phys. Rev. Lett.* **100** 015101 (2008)
57. Glyavin M Yu et al. *Radiophys. Quantum Electron.* **56** 497 (2014); *Izv. Vyssh. Uchebn. Zaved. Radiofiz.* **56** 550 (2013)
58. Read M et al., in *Strong Microwaves: Sources and Applications: Proc. of the 7th Intern. Workshop, Nizhny Novgorod, July 27 – August 2, 2008*
59. Zapevalov V E et al. *Radiophys. Quantum Electron.* **27** 846 (1984); *Izv. Vyssh. Uchebn. Zaved. Radiofiz.* **27** 1194 (1984)
60. Pavelyev V G, Tsimring S E, Zapevalov V E *Int. J. Electron.* **63** 379 (1987)
61. Zapevalov V E, Tsimring Sh E *Radiophys. Quantum Electron.* **33** 954 (1990); *Izv. Vyssh. Uchebn. Zaved. Radiofiz.* **33** 1288 (1990)
62. Zapevalov V E, Manuilov V N, Tsimring Sh E *Radiophys. Quantum Electron.* **34** 174 (1991); *Izv. Vyssh. Uchebn. Zaved. Radiofiz.* **34** 205 (1991)
63. Manuilov V N et al. *J. Infrared Millim. Terahertz Waves* **36** 1164 (2015)
64. Bratman V L, Kalynov Yu K, Manuilov V N *Phys. Rev. Lett.* **102** 245101 (2009)
65. Idehara T et al. *IEEE Trans. Plasma Sci.* **32** 903 (2004)
66. Booske J H et al. *IEEE Trans. Terahertz Sci. Technol.* **1** 54 (2011)
67. Griffin R G "High frequency dynamic nuclear polarization", in *Intern. Symp. on Development of Terahertz Gyrotrons and Applications, Univ. of Fukui, FIR-FU, 2013*
68. Wallace W P et al. *Appl. Spectrosc.* **60** 1127 (2006)
69. Miyoshi N et al., in *Proc. of the 34th Intern. Conf. on Infrared, Millimeter, and Terahertz Waves, IRMMW-THz, Busan, South Korea, 21 – 25 September 2009*
70. Nusinovich G S et al. *J. Appl. Phys.* **109** 083303 (2011)
71. Han S T et al., in *Proc. of 40th Intern. Conf. on Infrared, Millimeter and Terahertz Waves, IRMMW-THz, Hong Kong, China, 23 – 28 August 2015*
72. Oda Y et al., in *Proc. of 40th Intern. Conf. on Infrared, Millimeter and Terahertz Waves, IRMMW-THz, Hong Kong, China, 23 – 28 August 2015*
73. Saito T et al., in *Proc. of 40th Intern. Conf. on Infrared, Millimeter and Terahertz Waves, IRMMW-THz, Hong Kong, China, 23 – 28 August 2015*
74. Granatstein V L, Nusinovich G S *J. Appl. Phys.* **108** 063304 (2010)
75. Nusinovich G S et al. *J. Appl. Phys.* **111** 124912 (2012)
76. Glyavin M Yu et al. *Appl. Phys. Lett.* **105** 174101 (2014)
77. Miyazaki A et al. *J. Infrared Millim. Terahertz Waves* **35** 91 (2014)
78. Miyazaki A et al. *Prog. Theor. Exp. Phys.* 011C01 (2015)
79. Krupnov A F, in *Modern Aspects of Microwave Spectroscopy* (Ed. G W Chantry) (London: Academic Press, 1979) p. 217
80. Antakov I I et al. *JETP Lett.* **19** 329 (1974); *Pis'ma Zh. Eksp. Teor. Fiz.* **19** 634 (1974)
81. Tretyakov M Yu et al. *Instrum. Exp. Tech.* **51** 78 (2008); *Prib. Tekh. Eksp.* (1) 87 (2008)
82. Kazakov V P *Radiophys. Quantum Electron.* **23** 533 (1980); *Izv. Vyssh. Uchebn. Zaved. Radiofiz.* **23** 7 877 (1980)
83. Kazakov V P, Parshin V V, Dryagin Yu A *Izv. Vyssh. Uchebn. Zaved. Radiofiz.* **29** 240 (1986)