Invited Paper

The development of gyrotrons and their applications for plasma science and material processing

Yuri V. Bykov [1], Naum S. Ginzburg [1, 2], Mikhail Yu. Glyavin [1*, 2], Sergey V.Golubev [1], Grigory G. Denisov [1],
Alexey G.Luchinin [1], Vladimir N.Manuilov [2] and the IAP RAS - GYCOM team
[1] Institute of Applied Physics of the Russian Academy of Sciences, GYCOM Ltd. 46 Ul'yanov St., 603950 Nizhny Novgorod, Russia
[2] Nizhny Novgorod State University, 23 Gagarin Ave., 603950 Nizhny Novgorod, Russia
[*1] Email: glyavin@appl.sci-nnov.ru

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Abstract: The data about gyrotron-based technological systems and THz-band gyrotrons for diagnostics of different media are presented. The possible improvements of selective excitation of the operating modes with allowance for the competition with lower harmonics are considered. Double-beam electron optics is developed for a THz- band gyrotron. A sheet gyrotron as a tool for combining a high output power and frequency tuning is discussed. Long-life cathodes with additional heating by reflected electrons are preliminarily tested. 3D calculation of gyrotron operation regimes is carried out and the azimuthal inhomogeneity effects are analyzed. The results of experimental tests of a pulsed 200-*kW*/670-*GHz* gyrotron used for the initiation of localized gas discharge are presented.

Keywords: Gyrotron, Material processing, Terahertz, Multi-beam electron gun, Pulse field, Plasma discharge

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1. Introduction

In contrast to the classical devices of vacuum microwave electronics (magnetron, klystron, etc.), electrons in gyrodevices interact with the fields of the electrodynamic systems, whose characteristic sizes significantly exceed the wavelength. Furthermore, gyrodevices ensure efficient electronic and electrodynamic mode selection, which yields the regime of efficient high-power single-mode oscillation.

In terms of continuous-wave (CW) operation regime or average power in pulse mode, as well as radiation energy in long pulses, gyrodevices surpass significantly (by several orders of magnitude) other sources of millimeter- and submillimeter-wave radiation. Gyrodevices open up a new way for electron-cyclotron heating in controlled fusion (CF) facilities, the creation of a high-power radar, high-temperature material processing, diagnostics of various media, and other applications [1, 2].

2. Gyrotron-based technological systems

A CW gyrotron operated at the second cyclotron harmonic with a record-breaking efficiency of 60% at an output power of up to 10 *kW* [3] has been created at the IAP RAS to upgrade the gyrotron-based technological complexes. The achieved efficiency is ensured by using single-stage energy recovery and optimizing the distribution of the coil magnetic field.

Another important result is the creation of a gyrotron with rapid (2 *kHz*) stepwise tuning of the radiation frequency (by about 2%) by varying the magnetic field in the cavity with the help of an additional low-inductive coil. At a fixed frequency of generated radiation, the gyrotron can ensure a 100% modulation of the microwave power in the case of varied additional coil current [4]. The use of such a gyrotron has great prospects for the upgrade of the technological processes based on the use of microwaves, for example, generation of intense multi-charge ion beams and deposition of polycrystalline diamond from the gaseous phase of a discharge. The ceramic sintering technology based on a microwave technique has been used for laser ceramic ($Yd:Y_2O_3$, Yb:YAG, $Yb:(YLa)_2O_3$) sample sintering with optical transparency about 80%. These samples have successfully been used in the preliminary lasing experiments [5].

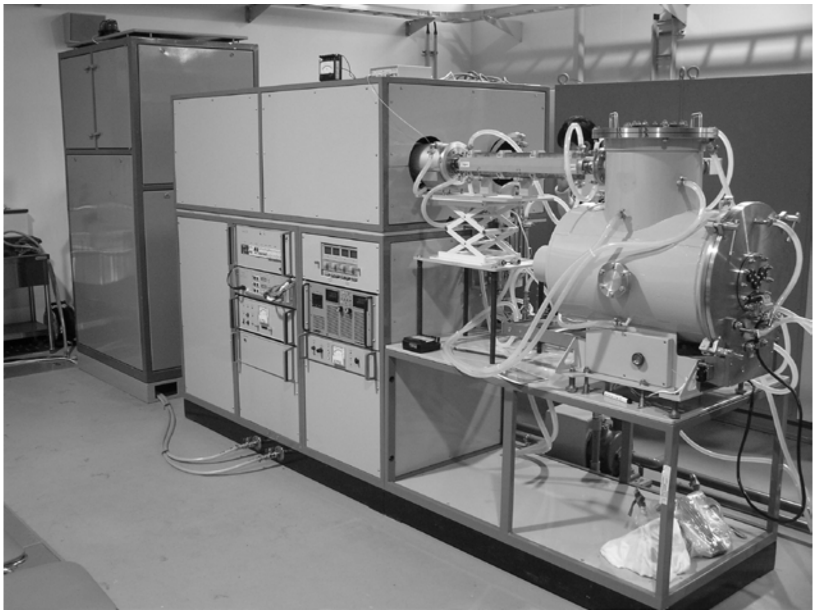

Fig. 1 The material processing complex with a gyrotron (15 *kW*/28 *GHz*) or a tunable gyro-BWO (2.5 *kW*/24±0.1 *GHz*) as radiation sources.

3. Long-life cathode development

Since all technological processes, as a rule, require a fairly long time (the characteristic time is from a few hours to a few weeks), it seems topical to create cathodes with increased lifetime because in most cases the lifetime of a device is determined by the durability of the cathode unit. A significant number of malfunctions are due to the lifetime of the heater.

It is well known that in a gyrotron the electrons move along helical gyrotrons and the trajectories of their guiding centers coincide with the magnetic field lines. By virtue of the electron velocity spread, which is an integral part of the magnetron-injection guns (MIGs) [6], part of the electrons with the largest rotational velocities are reflected from the magnetic mirror and come back to the cathode region. We found an electrode geometry in which the reflected electrons hit the cathode surface near the emitter, thereby contributing to the additional heating. The reflected beam does not affect significantly the velocity spread and a fraction of the gyration energy of electrons which are the main factors determining the oscillation efficiency. The problem was solved in a cycle of two steps, namely, by calculation of the electron beam parameters and determination of the electron hitting area and reflected beam power using EPOSR-T software [7] based on a dynamic axially symmetric model of the electron beam. Then, using QuickField software [8], we calculated the temperature distribution on the cathode and estimated the reduction of the required power of the heater with the emission current maintained. After this, the shape of the electrode was varied and a trajectory analysis was carried out again, etc. until the required electrode configuration was found to minimize the heater power and keep the electron beam parameters sufficient for the implementation of a high efficiency.

For an experimental verification of the possibility of reducing the glow when the cathode is hit by the reflected electron beam, we performed an experiment with a 28-*GHz* CW gyrotron. The maximum reduction of the heater power in the experiment was 22% [9].

Using the formulas for estimation of the heater durability [10], it is possible to compare the durability of the cathode with and without the hitting by electrons. The cathode lifetime was increased thrice when the hitting power was about 10 *W*. Of course, these estimates are very approximate. Moreover, the temperature of the cathode and the heater as parts of the device may differ from the value measured during pyrometering since the anode and other structural elements of the gyrotron can affect the temperature distribution over the cathode surface. If the heater temperature is 3000 *K* and its reduction due to hitting is again of the order of 200 *K*, then the described mechanism will yield a still greater gain, a factor of 6 to 7, in the cathode lifetime.

4. The possibilities of selective excitation of high-order modes at high cyclotron harmonics

In recent years, there has been increasing interest in the creation of high-frequency gyrotrons. High-power sources of sub-THz and THz radiation are required for the solution of a number of scientific and practical problems, such as, e.g., the localized-charge initiation in a plasma (for the problems of remote detection of ionized-radiation sources and in nanolithography), high-resolution spectroscopy and diagnostics, medical applications, etc. [11, 12]. The list of potential applications of such sources continues to extend rapidly. The gyrotrons, having a much greater (by several orders of magnitude) power compared with the classical electrovacuum oscillators (BWO, klystron, clynotron, etc.) and much smaller sizes and more costly than FELs, seem to be the most promising sources of microwave radiation in the frequency range 100-1000 *GHz*.

The methods of implementation of high-power gyrotrons depend considerably on the frequency range and operation regime (pulsed or CW). At frequencies of 100-300 *GHz*, the simplest and most efficient solution is operation at the first harmonic of the cyclotron frequency since the existing cryomagnets with 3-10 *T* fields are moderately priced and ensure the cyclotron resonance conditions $\omega = n\omega_H$ $(n=1,2,3\ldots)$ even at $n=1$. Here, ω is the operating frequency and ω_H is the cyclotron frequency. The use of the first harmonic significantly simplifies the selection of the spurious types of oscillation as well. However, in some topical problems (ECR plasma heating in the promising CF facilities of the next generation such as DEMO, diagnostics of dense plasmas by collective Thompson scattering, and some others), the selectivity of the currently used gyrotron circuits with powers more than 1 *MW* and in CW regime seems to be insufficient since it is necessary to go to operating modes of a very high order to ensure acceptable thermal loads on the cavity wall, which dramatically increases the number of modes in the cyclotron resonance band. It seems that the selectivity of spatially developed systems can be increased by using the planar geometry of the interaction space proposed in [13]. The advantage of this scheme compared with the conventional cylindrical geometry of gyrotrons is the possibility of providing coherent radiation with a large oversize factor due to the diffraction mechanism of mode selection on the open transverse coordinate and synchronizing the radiation of different fractions of a sheet helical electron beam (HEB) by transverse energy flows. In this case, it seems expedient to use a planar geometry instead of the conventional tubular geometry of polyhelical electron beams to maintain the efficiency of energy exchange. The linear size of the beam can be a factor of 50 or more, greater than the wavelength, thereby increasing the radiated power with the preservation of a moderate density of the beam current and field intensity. For a planar gyrotron, we developed an electron-optical system creating an electron beam with the pitch factor g=1.3 and an electron velocity spread of 25-30% [14]. According to calculations, this enables single-mode oscillation with efficiency close to typical values in the conventional gyrotrons without the energy recovery (about 30-35%) for the gyrotron with an operating frequency of 140 *GHz* and a beam power of 1.5-2 *MW*.

The increasing frequency of CW gyrotrons (400-1000 *GHz*) makes it a problem of priority to pass to the harmonics of gyrofrequency $(n=2,3)$ since the existing line of cryomagnets with acceptable sizes and cost ends at fields of 12-15 *T*, and at fields of more than 20 *T* the widely available sources of the magnetic field are absent at all. Operation at the gyrofrequency harmonics is known to exacerbate drastically the mode competition problem because the modes that are synchronous with the beam at the lower harmonics are also involved in the process. An effective way to improve the selection of conventional gyrotrons is transition from single-beam to multi-beam circuits. Experience in the multi-beam gyrotron development [15, 16] allows us to hope for a two- or threefold increase in the gyrotron output when the current of the additional HEB is 10-20% of the current of the main beam, or to hope, with the gyrotron power kept at the same level, for a significant increase in the operating frequency of the device by increasing the selective properties of the system. Figure 2 shows the geometry of the electrodes of a double-beam CW gyrotron with an operating frequency of 1000 *GHz* and an output power of about 1*kW*.

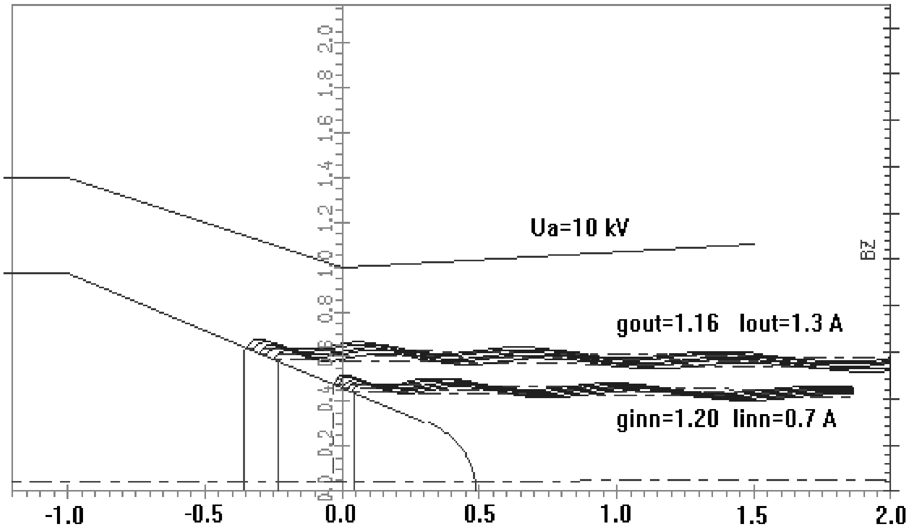

Fig. 2 Schematic view of a double-beam MIG of a 1-*THz* gyrotron.

As the operating mode at the third cyclotron harmonic we propose the $TE_{9,7}$ mode. Preliminary analysis of the scenario of the oscillation buildup shows the possibility of selective excitation of this mode and the possibility of practical implementation of the synthesized double-beam system of the HEB generation with close pitch factors of both beams (g=1.3) and a moderate velocity spread.

4. Numerical modeling of gyrotrons

The complication of the scenario for mode competition and operating-mode onset in passing to the subterahertz band requires the use of an increasingly more accurate physical model of the electron-wave interaction. Calculation procedure for the current-voltage characteristic of the gyrotron MIG [17] is based on calculation of the electron beam parameters in the regime of a space-charge limited current and temperature-limited emission current by matching the solutions at the point $U = U_\rho$ where the emitter field is zero (the transition from one regime to another). This permits us to describe more exactly the beam characteristics at the leading edge of the accelerating voltage pulse and thereby simulate more accurately the process of entering the stationary oscillation regime.

By convention, the analysis of interaction between a helical electron beam and the field of the electrodynamic system is based on the averaging technique, which is used to solve the equations of an ensemble of nonlinear oscillators affected by a force averaged over the period of the microwave field and acting from the limited number of modes entering the cyclotron resonance band. However, this approach has constraints such as the assumption of exact fulfillment of the axial symmetry conditions for the cavity and the electron beam, preset number of modes involved in the interaction, etc. At the same time, the characteristic sizes of the electrodynamic system decrease with decreasing wavelength of the radiation. Correspondingly, the role of the spatial azimuthal nonuniformity of the electron current increases, and so do the cavity manufacturing errors (in particular, that the cross-sectional shape of the cavity is different from cylindrical). Calculation of the oscillation regimes with allowance for these factors can be performed by using advanced 3D commercial codes such as CST Studio. Comparison of the results of the calculations for a 1-*THz* $TE_{17,4}$-mode gyrotron and the experimental data confirmed the possibility of reliable modeling of gyrotrons with different-geometry cavities at frequencies of up to about 1 *THz* while maintaining a reasonable time of count and computer resources [18]. The calculation results demonstrating the structure and power of oscillations as functions of the magnetic field in the interaction space for the gyrotron with a cylindrical cavity are presented in Fig. 3. It should be mentioned that modern PIC codes open up a possibility for 3D modeling of gyrotrons with allowance for the effects related to the azimuthal nonuniformity of the electrodynamic system and electron flow. In particular, the influence of the emission nonuniformity and the electron beam displacement on the gyrotron efficiency were evaluated. Preliminary estimates show that these effects may lead to a decrease in efficiency by 15-20% of the initial value.

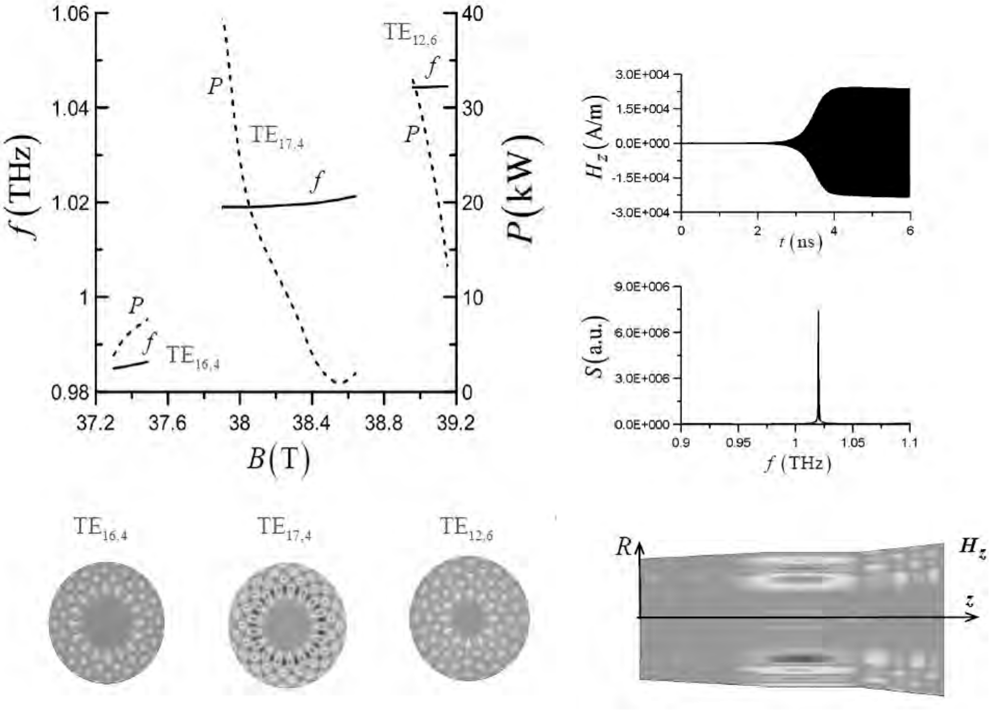

Fig. 3 The result of numerical modeling of a 1-*THz* gyrotron with operation regimes.

5. High-power pulsed gyrotrons for plasma experiments

The gyrotron operated in the regime of short (tens or hundreds of microseconds) pulses permits the use of oscillation with $n=1$ at frequencies of up to about 1 *THz* since a high-intensity magnetic field can be created by pulsed coils. In 2011-2012, the IAP RAS researchers developed and tested a gyrotron based on a nitrogen-cooled pulsed coil, in which stable single-mode generation of a high-order operating mode ($TE_{31,8}$) for an output power of 200 *kW* and a microwave pulse duration of 30 μs [19] was reached at a frequency of 670 *GHz*. The gyrotron circuit and typical oscillograms of the detector signal, voltage, and electron-beam current are presented in Fig. 4.

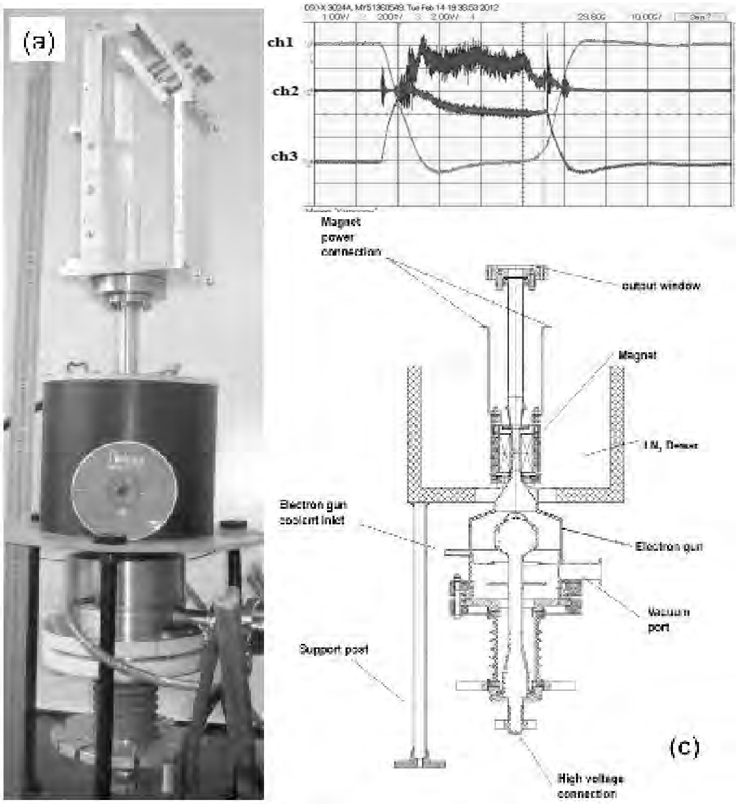

Fig. 4 A photograph and general view of the gyrotron with an operating frequency of 0.67 *THz* based on a pulsed coil [19]. The oscilloscope traces of beam voltage (ch1), beam current (ch2), and microwave signal from detector (ch3) in the maximum -power regime

The microwave pulse energy was determined by the calorimetric method using a calorimeter described in [20] and having a sensitivity of about 0.1 *J* in the single-pulse regime. The pulse repetition rate was limited to the rate of cooling of the coil immersed into a container with liquid nitrogen, which was about one pulse per minute. A narrow directed wave beam was formed using an external quasi-optical converter to obtain a discharge with a characteristic size of about 2 *mm* in a wide range of pressures (from 1 to 0.1 *atm*) in argon [21]. The possibility of obtaining such a localized discharge seems promising for a number of applications, in particular, high-resolution lithography [22] and remote detection of ionizing radiation sources [23].

A photograph of the discharge obtained using this gyrotron is shown in Fig. 5. The characteristic size of the discharge area (bright spot located in the focus of a short-focus parabolic mirror, half of which is cut for imaging), which is about 1 *mm*. According to the measurements by a PIN diode, the EUV radiation power is estimated as 1.5 *kW* [22]. Further experiments with the gyrotron will aim at precise measurements of the oscillation frequency, optimization of the quasi-optical converter of the gyrotron radiation into a wave beam, determination of the spatial structure of the radiation, obtaining a breakdown in air under atmospheric pressure using additional focusing mirrors, study of the gas-discharge dynamics, and implementation of the oscillation regime of a sequence of microwave pulses on the shelf of a single pulse of the magnetic field.

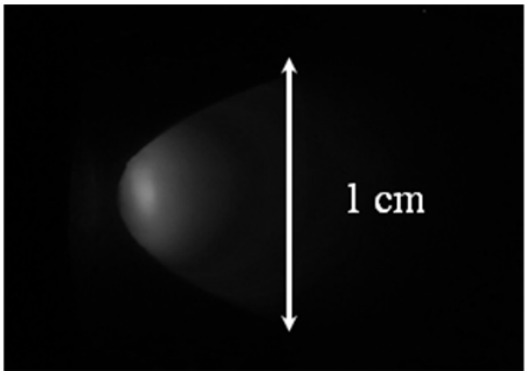

Fig. 5 The discharge in argon with a pressure of about $5*10^{-3}$ *Torr*. The discharge zone corresponds to the white color area about 1 *mm* in diameter, which is located in the mirror focal plane. The gray color is a backlight of the mirror surface by visible light.

The estimates show that high-power submillimeter-wave gyrotrons open up new prospects for active diagnostics of plasmas by the methods of collective scattering. However, the practical implementation of the proposed approach in most of the existing gyrotrons requires increasing either the pulse repetition rate or the pulse duration. The 600-700 *GHz* range seems the best for plasma diagnostics with temperatures of up to 10 *keV*. Diagnostics of the higher temperatures is not yet available. It should be mentioned that according to the calculations, the gyrotrons operated at frequencies of about 1 *THz* or higher do not give sufficient advantages in plasma diagnostics because of the rapid increase in the background electron-cyclotron radiation intensity at the harmonics [24].

6. Conclusion

In recent years, new technologies based on high-power microwaves have appeared in material processing and plasma physics. Progress in the development of gyrotrons and their applications will be continued and accelerated in the coming years. Experimental tests of proposed schemes to extend the future of gyrotrons are planned.

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