Invited Paper

THz Gyrotrons: Status and Possible Optimizations

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Abstract: The state of the art of THz gyrotrons is briefly discussed. The possible optimizations of the magnetron injection gun and electrodynamics system for THz gyrotrons are discussed. The electron optical systems with extraction of reflected electrons are presented. The significant increasing of electrons transverse energy predicted in theory and confirmed by experiments. In order to increase the integral output power, it is suggested using a planar gyrotron scheme with a high oversized factor. The results of nonlinear dynamics simulation show that in such scheme it is possible to reach an output power of several hundred kilowatts at sub-THz band with a fine frequency tuning by changing the distance between plates.

Keywords: Terahertz, Gyrotron, Electron gun with extraction of reflected electrons, Planar scheme

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1. Introduction

At present, there is a strong interest in developing powerful sources of the terahertz radiation for numerous scientific and technological applications as well as spectroscopy, plasma diagnostics, communication, medicine etc. (see, for example, [1-5]). Among the existing sub-THz and THz sources, one of the most promising are gyrotrons. In comparison with Cherenkov devices (like BWOs and orotrons), terahertz gyrotrons can provide a higher level of average power. At the same time, unlike FELs, gyrotrons can operate with electron beams having significantly lower energies of 10-100 keV. Correspondingly, they are much more compact than FELs and available for many laboratories.

The operation frequency of gyrotron can be estimated as $f(THz) \approx 0.028\, B(T)\, n/\gamma_0$, where n – number of cyclotron harmonic, γ_0 - relativistic factor. For high harmonic operation, the special methods of mode selection needed, so the progress in gyrotrons frequency increasing is limited, first of all for fundamental operation, by possibility of realization of sufficiently strong magnetic fields. Typical magnetic fields, which can be produced in modern cryomagnets with a large enough inner bore, do not exceed 15-20 T [6]. Such fields can be used in THz gyrotrons operated at high cyclotron harmonics, which, in turn, runs into rather complicated problems of mode competition and Ohmic losses. However, this approach has no alternative for development of CW terahertz sources with power levels of hundreds watts. The combined magnetic systems are capable of providing DC fields up to 40 T [7], but, at the same time, have an extremely high power consumption up to tens MW. Correspondingly, such systems cannot be available for widespread use. At present time, the simplest and cheapest method for obtaining strong magnetic fields to study and optimization of terahertz high power gyrotrons is presented by pulsed magnets. In principle, these systems can provide magnetic fields with intensity above 90*T* [8-9]. Pulsed solenoids with field of 40-50 *T* can be relatively compact and at low-cost [10].

Despite the above problems associated with the creation of strong magnetic fields, THz gyrotrons have been realized in many laboratories. The detailed review of the present status of THz gyrotrons can be found, for example, at manuscripts [11-16]. Now only a brief description of recently published experimental results and some prospects from sub-terahertz and terahertz gyrotrons will be given. The paper is organized as follows. In Section 2 main results of THz gyrotrons development and applications are given. In Section 3 the experimental results of frequency and power control in gyrotron based on magnetic field variation by additional low inductance coil has been presented. In Section 4 the possibility of magnetron injection gun optimization due to extraction of electrons, reflected from magnetic mirror is analyzed. In such electron optical systems the beam with high rotation energy of particles can be formed and as a result the gyrotron efficiency can be increased substantially. The possibility of significant reduction of operating voltage is discussed. Section 5 is focused on the description of the novel planar gyrotron scheme with a high oversized factor.

2. Some results of THz gyrotrons development and applications

First successful experiments with sub-terahertz gyrotrons were carried out at the IAP (Russia) in the 1970-1980*s*. In those experiments CW second-harmonic operation at a frequency of 0.33 *THz* with a power of 1.5 *kW* [17] and fundamental-harmonic operation in 50 microseconds pulses with a power of 40 *kW* at a frequency of up to 0.65 *THz* [18] were demonstrated. Other important achievements at the first stage of high-frequency gyrotron development have been the realization of mechanical variation of cavity size, which opened the basic opportunity for broadband and smooth frequency tuning [19], and successful test of multi electron beams gyrotrons, which gave a chance to improve mode selection [20].

A high output power of 375 *kW* at the frequency of 0.33 *THz* has been obtained in 3 microseconds pulses in the Massachusetts Institute of Technology (MIT) [21]. Current MIT efforts in the THz frequency range are basically concentrated on gyrotron development for DNP experiments [22-23]. In this direction, CW operation at a frequency of 0.23 *THz* with the power 10 *W* at the lowest voltage of 3.5 *kV* was obtained at the fundamental harmonic [24]. A stable, long term (21 day) operation was demonstrated. In addition, broadband and continuous frequency tuning of the fundamental-harmonic gyrotron over a range of more than 2 *GHz*, which was based on the excitation of opposite waves and smooth transitions between the axial modes of a low-Q cavity during variations of the magnetic field, was demonstrated [25]. A similar method was also used for the 0.14 *THz* gyrotron at FIR [26]. Initially, the possibility of this mechanism was studied theoretically in [27].

Successive development of medium-power high-frequency FU Series gyrotrons at Fukui University demonstrated frequency step-tunability in a very wide range, namely, from 38 *GHz* to 0.89 *THz*, including the excitation of the second cyclotron harmonic in 17-T solenoid with frequency 0.89 *THz* [28]. The gyrotrons of this series have been used as radiation sources for several electron spin resonance (ESR) experiments, for plasma scattering measurements and

X-ray detected magnetic resonance (XDMR) as well as for the study of such important physical phenomena as mode interaction (competition, cooperation, mode switching), frequency and amplitude modulation, frequency step switching, operation at high harmonics and with high mode purity, stabilization of the output parameters and operation for long periods of time etc. All these tubes are being operated in a pulsed mode with pulse lengths of the order of milliseconds, repetition rate of the order of several Hz, and duty ratio of several percent. Second-harmonic low-power gyrotrons with frequencies 0.15-0.6 *THz* were also demonstrated in joint experiments of the FIR and the University of Sydney [29].

In modern experiments, the radiation frequency of pulsed gyrotrons was increased up to 1.3 and 1 *THz* at the fundamental and third cyclotron harmonics, respectively. First break through magic 1 *THz* mark has been obtained at 2006 by FIR FU team, Fukui, Japan [30]. The pulsed solenoid based on an original ice-protected technology with maximum field intensity about 20 *T* was used; the excitation of several modes at fundamental and second harmonics was demonstrated. At the second harmonic the frequency 1.002 *THz* was achieved. The possibility of long pulse (1 *ms*) operation was shown. At the same time fundamental harmonic gyrotrons with a pulsed coil was developed at IAP RAS [31]. These gyrotrons are the most powerful pulsed THz tubes. The power 1 *kW* at 1.02 *THz* with 50 microseconds pulse duration was obtained. Further optimization of electron optics and pulsed coil gave the possibility to increase power at 1 *THz* up to 5 *kW* and realize 0.5 *kW* at 1.3 *THz*. At present, 100 *kW* level gyrotrons with operating frequency 0.67 *GHz* with pulsed coil have been developed for remote (several tens meters) detection of concealed sources of ionizing radiation [32]. In preliminary experiments, the power of 100 *kW* is already demonstrated [33]. In 2008, the third harmonic 1 *THz* gyrotrons with improved mode selection has been realized at IAP RAS [34]. The excitation of third harmonic was implemented due to axis-encircling electron beam (so called Large Orbit Gyrotron-LOG). In this oscillator, an electron-optical system with a cusp gun and a following then drift section of adiabatic magnetic compression with a factor of 3,000 provided the formation of the 80 *keV*/0.7 *A* beam of axis-encircling electrons with admissible velocity and position spread in a wide range of voltages and magnetic fields. Stable single-mode generation with a power of 0.3-1.8 *kW* in 10 microseconds pulses was detected in the range 1.00-0.55 *THz* at resonant magnetic fields in the region of 10.5-14 *T*. The oscillator operated with repetition rate 0.1 *Hz*. This THz LOG has been used in experiment for initiation of gas breakdown that allows realizing high density plasma with dimensions of about a few millimeters. It can be promising for creation of the high-power point source of multi-charged ions and/or extreme ultraviolet [35]. It is important to mention, that some theoretical estimation predict the possibility of high repetition rate (up to 2 *Hz*) with a field about 40 *T* [36]. To conclude description of pulsed tubes, let us keep in mind the Chinese 0.4 *THz* tube with power about 5 *kW* at second cyclotron harmonic [37]. All mentioned projects now are under development with the goals to increase power, frequency and repetition rate.

It is well known, that many potential applications require continuous (CW) radiation of terahertz range for long time. Such demand motivates the development of the CW gyrotron. Magnetic field with intensity of 10-15 *T* for these gyrotrons is produced in superconducting magnet. Because of the complexity of producing strong DC magnetic fields, most gyrotrons operated in this range are developed at the cyclotron-frequency harmonics. Significant progress in the development of CW THz gyrotrons for the various applications has been achieved in FIR FU (Japan). A chain of tubes [16] (namely the Gyrotron FU CW) have been developed in the frame of research program devoted to NMR-DNP spectroscopy. The principle of this technique is to increase the signal to noise ratio and thus the overall sensitivity by transferring the large electron spin polarization to the nuclear (proton) spin irradiating the studied sample with a microwave radiation with a frequency equal or close to the electron paramagnetic resonance frequency. Theoretically enhancements about two orders of magnitude are possible. In practice, however, the results depends on many factors and most notably on the quality of the microwave source output parameters, e.g. power about several watts at the irradiated sample; long time stability of power and frequency; frequency tunability in a wide range; mode purity.

Gyrotron FU CW I has been developed in collaboration with GYCOM (Russia) and realized 2.5 *kW* CW operation with 0.3 *THz* frequency [38]. This is an industrial tube with internal mode converter and record CW power in this range. Several FU CW gyrotrons have been used in a process of preparation for DNP/NMR experiments (gyrotron frequency 0.39 *THz*, power about 100 *W*) and direct measurement of the hyper-fine splitting (HFS) of positronium (gyrotron frequency 0.2 *THz*, power up to 400 *W*). FU CW C (compact) and FU CW G (gaussian beam, i.e. gyrotron with internal mode converter) gyrotrons based on the utilization of compact liquid He-free superconducting magnets are under development. This concept has been realized recently in FU CW CI [39], which has been built using an 8 *T* magnet with 52 *mm* hot bore. It delivers radiation for DNP-NMR spectroscopy experiments with a frequency around 0.395 *THz* at the second harmonic. The FU CW GI tube has an internal mode converter which consists of simplest Vlasov launcher and four mirrors and operates at 0.2 *THz* fundamental harmonic. The next tube, FU CW GII has a similar design but will operate at the second harmonic resonance. The design of FU CW CII tube also includes internal mode converter and the target parameters are frequency of 203.4 *GHz* and output power of 500 *W*. It is optimized for experiments on the direct measurements of the hyperfine structure of positronium.

As a result of THz gyrotron development at USA (MIT and CPI), the world's first commercially available solid-state DNP-NMR spectrometer AVANCE™ III [40] has been created. Signal enhancements from 20 to a factor of 80 on multiple samples are possible and system optimization is ongoing for even higher DNP efficiency. The 50 *W/CW* gyrotron, delivering microwaves at 0.26 *THz*, is robust, safe and easy-to-use, enabling long term DNP experiments without time limits.

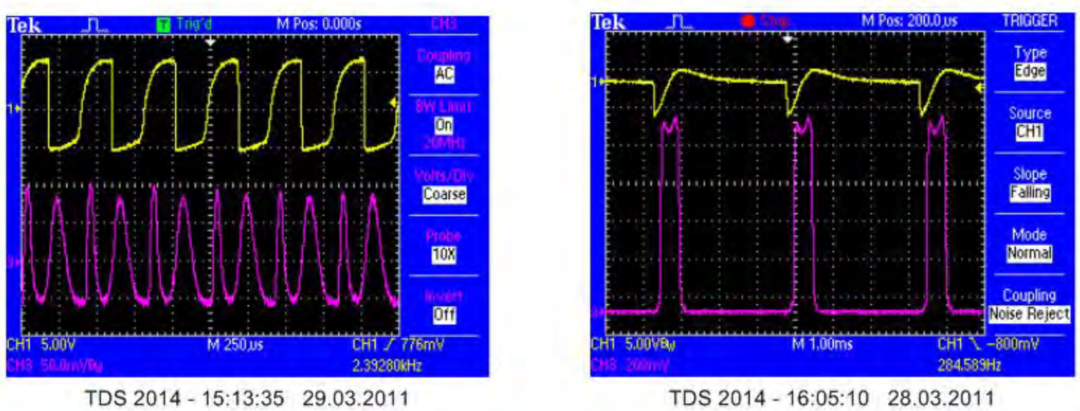
At present, CW second harmonic gyrotron with frequency of 0.26 *THz* has been realized in IAP for DNP/NMR spectroscopy complex [41]. The main requirements for this device were an ensured output power of about 100 *W* and high frequency stability at the level 10^{-5} during a sufficiently long period (about 12 *h*). The transmission line includes external mode converter and gyrotron which is used for DNP/NMR spectroscopy.

3. Gyrotron with the wide-band fast frequency sweeping

Some applications, such as, driving an electron cyclotron resonance ion sources, requires the fast (1 *kHz*) and wide band (2-3%) frequency tuning. Such wide-band frequency tuning is impossible in resonance zone of single mode due to high gyrotron cavity Q-factor ($\sim 10^3$) and can be realized by magnetic field variation with mode switching. For this goal two points are important: for coil with inductance L and resistance R character time t=L/R must be small enough and skin effect in the gyrotron body must be minimized. The second harmonic K-band gyrotron was developed to solve this problem. Additional coil consists of several tens turns wired directly on the tube body in the cavity region. The coil current about 10 *A* needs for 2% magnetic field variation in presence of main field (B_0≈0.5 *T*) at second harmonic 0.03 *THz* operation. The output power about 10 *kW* and efficiency 20%, close to calculated one, were obtained for both modes at 24 *kV*/2.2*A* operating regime. The experimental results [42] are shown in figure 1.

The frequency difference for operated modes $TE_{2,3}$ and $TE_{0,3}$ is close to 2%. The alternation of maxima in the figure 1 (a) corresponds to switching from one mode to another - even maxima correspond to the same frequency, odd – other frequency. The possibility of fast power modulation is demonstrated in figure 1 (b).

Within the operation zone of a single mode the frequency sensitivity to additional coil current is about 2 *MHz* to 0.1 *A*. This fact gives a chance for frequency stabilization due to feedback signal and precise frequency control. The method needs much more simple and cheap power supply in contrast with anode voltage control, but, of course, has some additional limitation. This scheme can be used for any gyrotrons, including sub-THz and THz band. At present, similar scheme is under operation tests at Japan for powerful gyrotrons for nuclear fusion [43].



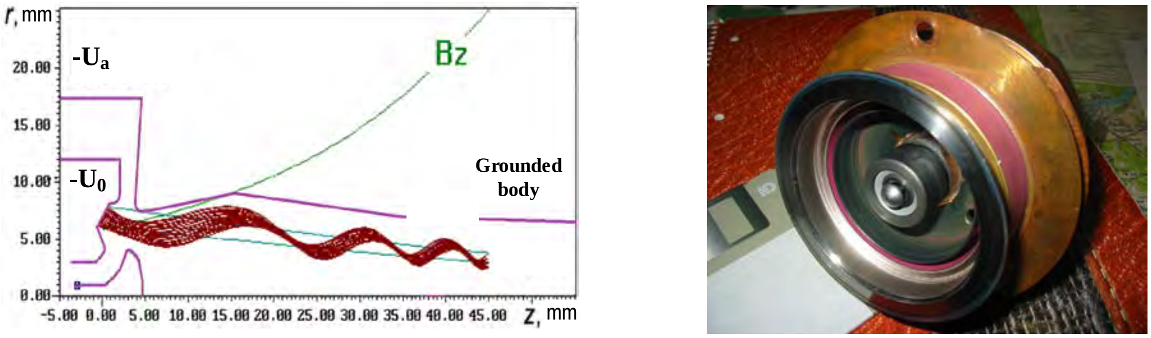
(a) (b)

Fig. 1 Tunable gyrotron experimental data: frequency switching between modes (a) and power modulation (b)

4. Electron guns with extraction of reflected electrons

In gyrotrons the magnetron-injection guns (MIGs) are usually used to form the helical electrons beams (HEBs) with suitable beam quality. Well known disadvantages of MIGs are strong influence of the emitter roughness on the velocity spread and uncontrolled increasing of the emitter current caused by the electrons reflected from the magnetic mirror. These factors limit the maximum achievable value of pitch-factor considerably. Described disadvantages of traditional MIGs can be eliminated if we switch from temperature limited regime to the space charge limited regime.

Below the results of numerical optimization and experimental tests of the low-voltage non-adiabatic formation systems (NAFS) are presented. The schematic view of the MIG is shown in figure 2(a) and photo of the MIG is presented in figure 2 (b).

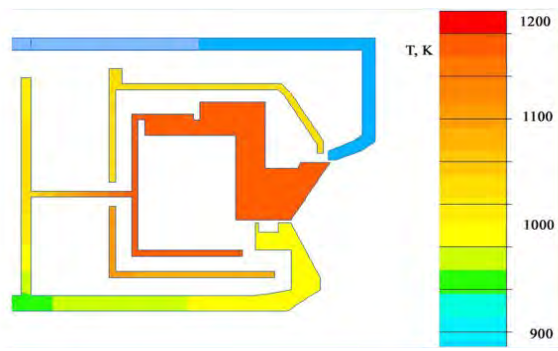


(a) (b)

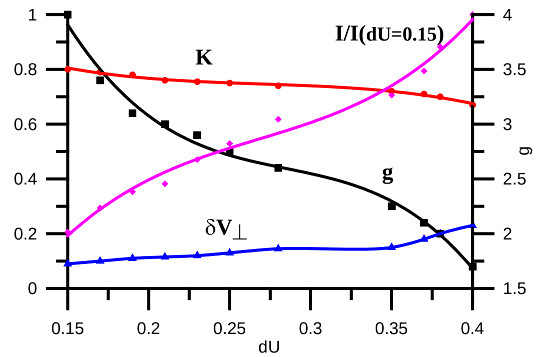
Fig. 2 NAFS geometry and photo, electron beam trajectory and axial magnetic field distribution *B*z.

The injector of the electron gun consists of a concave annular cathode, partially covered with the emitting layer, and two anodes – internal and external. The magnetic field in the gun region is the scattering field of the main solenoid, which forms the magnetic field in the cavity region. For correction the magnetic field in the gun region a relatively low-power additional solenoid is used. In the considered gun, the influence of nonuniformities of the emitter electric field and the spatial charge field is excluded or considerably decreased. Firstly, the gun operates in the mode of total spatial charge, and, therefore, the electric field on the surface of a virtual cathode in such a gun is zero, and so small-scale inhomogeneities of the surface and the emissive properties of the cathode are not important for the beam formation. Secondly, the anodes of the gun are located both outside and inside the electron-motion area, which makes it possible to exclude or drastically decrease the difference of the electric field on the inner and outer boundaries of the electron beam. All these factors reduce the velocity spread in comparison with traditional magnetron-injection gun and give a chance to increase transverse energy of an electron beam. The gun is aimed to be used in the 0.03 *THz* gyrotron with the output power of 3-5 *kW* (U_0=5 *kV*, I_0=3*A*, calculated efficiency without depressed collector about 20%). It is necessary to note, that the specific feature of the gun is of very high value of the perveance $10^{-5} A/V^{3/2}$ that is at least in order of magnitude higher than that in traditional MIGs.

Numerical simulation of the gun was performed within two-dimensional static model using the code EPOS [44]. According to the calculations, the gun provides moderate value of the oscillatory velocity spread $\delta v_{\perp}$=14% for high HEB pitch factor *g*=1.8. The numerical analysis has shown the possibility to use the NAFS also for high frequency gyrotrons. The measurements of the beam parameters were carried out by the well known retarding potential method. Preliminary experimental investigation of the beam properties was carried out with the diode configuration of the gun. It was found that in the initial gun design the essential part of the current is intersected by the upper anode. According to the experimental data and the numerical simulation, one of the possible reasons is the parasitic emission from the cathode region near the emitter. To verify it, the calculation of the heat transfer inside the gun body by the QuickField™ simulation software [45] was carried out. The calculated temperature distribution on the cathode is shown in figure 3(a). Using this data the thermal isolation of the cathode parts was upgraded and additional anti-emission coating was evaporated near the emitter. The gun is also sensitive to positioning in the magnetic field and, so, the required installation accuracy (including possible temperature drift) looks close to 0.1 *mm*. To reduce the intersection of the electron beam, the outer anode shape was slightly altered and the outer anode diameter near the end of the first trajectory step was increased. Along with that, to minimize the effects of misalignment and increase the control over the electron beam, the configuration of the electron gun was changed to the triode one. It allows decreasing of the emitter bombardment by the reflected electrons and caused by this factor secondary emission.



(a)



(b)

Fig. 3 Temperature distribution on the cathode (a) and measured dependencies (b) of the K value, pitch-factor g, velocity spread and total beam current vs. relative anode-cathode voltage dU = (U_0 - U_a) / U_0 in the scaling regime (scale coefficient U/U_{scale}=10)

After modification of the gun geometry and manufacturing technology, it was possible to form the HEB with pitch-factor $g>2$, velocity spread less than 15% and suitable (70% or more) ratio of the passing to the cavity current to the cathode one – $K=I_{cavity}/I_{cathode}$ (figure 3(b)).The NAFS looks suitable for medium power gyrotrons for spectroscopy applications. Despite the high sensitivity to the positioning accuracy, such systems may provide significantly better beam quality than traditional adiabatic MIGs and operate with low voltage. The possibility of low (several *kV*) voltage gyrotron operation was predicted theoretically [46] and demonstrated in experiments [26]. The low voltage simplifies the scheme of the system and makes it smaller and less heavy, significantly reduces the x-ray radiation from the collector and, after all, makes it much cheaper. Below brief estimation of output parameters of *kW* level 0.2 *THz* gyrotron for hyperfine structure measurement on positronium is given. For fundamental harmonic, it is possible to found the mode, good separated from parasitic one. The calculated output power versus accelerating voltage for 0.5*A* beam current and 14 *mm* cavity length is shown in figure 4. The 100 *W* output power can be obtained for voltage lower than 4*kV* and 250 *W* for 5*kV* even if pitch-factor equal to 1. Such situation looks very attractive for the compact, cheap and useful for any laboratory power supply and gyrotron complexes.

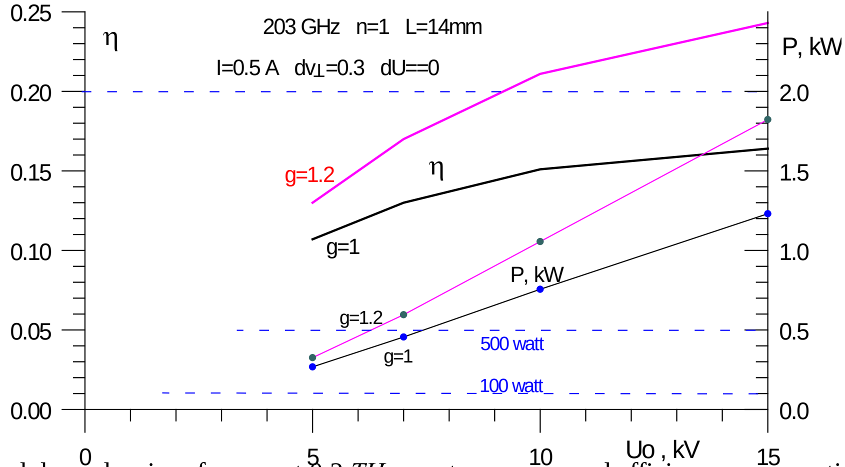


Fig. 4 Calculated dependencies of compact 0.2 *THz* gyrotron power and efficiency vs. operating voltage

5. The gyrotron with a planar cavity

For drastic increase in output power of short wavelength gyrotrons a planar scheme with a sheet electron beam and transverse (with respect to electrons longitudinal velocity) electromagnetic energy extraction has been suggested [47]. The main advantage of this novel concept in comparison with conventional cylindrical gyrotron geometry is the possibility to ensure coherent radiation from a large size planar electron beam due to effective mode selection over the open transverse coordinate and synchronization of radiation from different beam fractions by transverse electromagnetic energy fluxes. As a result the power of the gyrotron can be significantly increased for moderate density of current and field intensity. Simultaneously effective transverse energy extraction from the interaction space leads to decreasing diffraction Q-factor, that essentially reduces the relative share of Ohmic losses. Moreover, with extension of the electron beam, it is beneficial to increase the wave group transverse velocity at the edges of the interaction space by proper tapering of the gap between the waveguide plates. The resonators of similar profile are known as unstable resonators in optics where they are exploited for increasing of radiation power in some types of lasers. Alongside with an increase in the radiation power, effective frequency detuning in the suggested gyrotron can be realized by mechanical variation of mean gap between plates.

The microwave system for the suggested gyrotron is formed by a planar waveguide with a regular or smoothly tapered transverse profile. The gyrotron is driven by a sheet beam of electrons rotating in a homogenous magnetic field (z axis). The resonator is open for energy extraction in the transverse direction (x axis). Effective mode selection along x coordinate is caused by the difference in diffraction losses for modes with a different number of transverse variations. In contrast with conventional schemes we assume that in the axial z direction the cavity is closed by cutoff necks. Mode selection over the second transverse coordinate (y axis) may be achieved when the frequency distance between neighboring cut-off modes exceeds the cyclotron resonance band: $c\pi/b \geq \omega/2N$, where b is the distance between plates and N is the number of cyclotron rotations on the interaction length. Thus an acceptable gap between plates satisfies the following condition: $b \leq N\lambda$. Note that in conventional gyrotrons with a closed cylindrical resonator with radius R the similar criteria $R \le \sqrt{N/2\pi^2}\lambda$ results in more severe restriction for the transverse size. Simulations of the nonlinear dynamics of the planar gyrotron with a polyhelical ribbon electron beam were performed for an operating frequency of 1 *THz*, an accelerating voltage of 30 *kV*, a pitch-factor g=1 and a distance between plates about 30λ. For a rather small size of electron beam the output power grows with increasing of the beam width and the total current up to beam size about 50λ. Future increasing of the width leads to only ohmic losses rise. For optimal generator length total efficiency is η~20%. Taking into account that about 30% of total radiation power is dissipated in Ohmic losses the output power is estimated to be 100 *kW* level.

As a first experimental revision of proposed scheme, the 0.08 *THz* project has been initiated at IAR RAS in collaboration with IRE NANU (Kharkov, Ukraine). The results of numerical simulations are shown in figure 5 (a-d). The calculations predict the single mode operation with output power level about 0.5 *kW* with 6*kV*/0.3*A* electron beam. The magnetic system and planar MIG are under development.

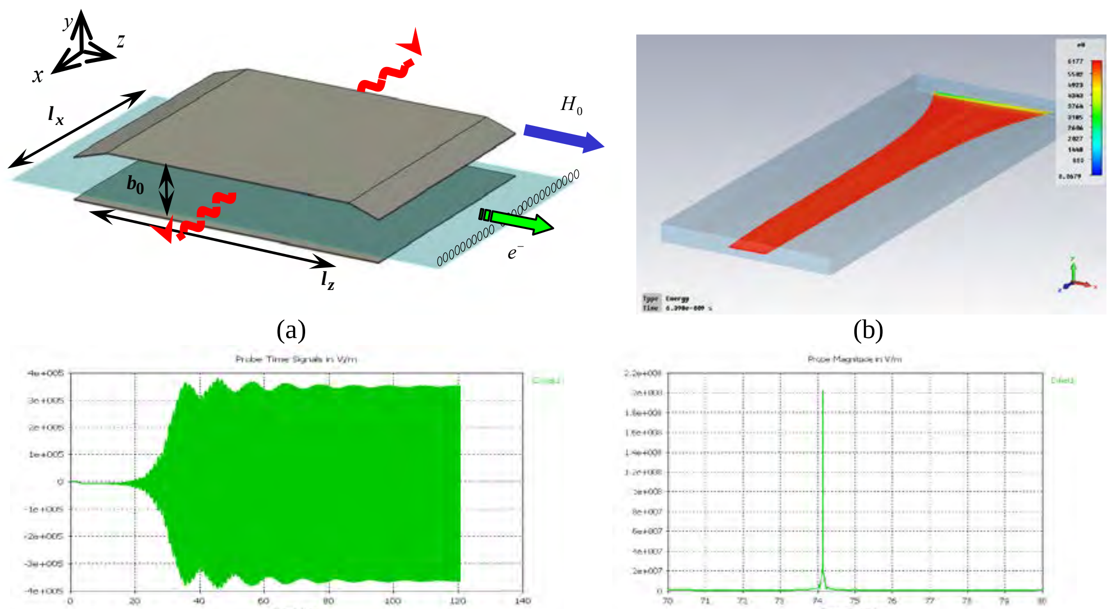


Fig. 5 The general view of cavity (a), beam profile (b), microwave signal evolution versus time (c) and frequency spectrum of steady-state regime (d) for planar gyrotron

6. Conclusion

In recent years gyrotrons have demonstrated a remarkable potential for bridging the THz power gap and have been used in a great and continuously increasing number of applications. The progress in the field of the development and application of sub-terahertz and terahertz gyrotrons will be continued and must be accelerated in the coming years. Therefore the experimental tests of proposed schemes to extend future of gyrotrons are planning.

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References

[1] P.H. Siegel, *IEEE Trans*. *Terahertz Sci. & Technol*., 1, 1 (2011)

[2] P.H. Siegel, *IEEE Trans*. *Microwawe Theory & Techn*., 52, 2438 (2004)

[3] J.H. Booske, *Phys Plasmas*, 15, 1 (2008)

[4] D.L.Woolard, E.R. Brown, M. Pepper, M. Kemp, Proc. *IEEE*, 93, 1722 (2005)

[5] E. Linfield, *Nature Photon*., 1, 257 (2007)

[6] http://www.jastec-inc.com/e_products_cryogen/index.html

[7] A. Bourquard, D. Bresson, A. Daël et al., *J. of Low Temperature Physics*, 159, 332 (2010)

[8] T. Feder. *Physics today*, 64, 11, 25 (2011)

[9] http://www.lanl.gov/news/releases/los alamos_achieves_world_record_pulsed_magnetic_field.html

[10] M.Yu. Glyavin, K.A. Zhurin, E.A. Kopelovich et al., *Instr. & Experimental Techniques*, 54, 77 (2011)

[11] T. Idehara, I. Ogawa, T. Saito et al., *Terahertz Sci. & Technology*, 1, 100 (2008)

[12] V. Bratman, M. Glyavin, T. Idehara et al., *IEEE Trans. Plasma Sci*., 37, 36 (2009)

[13] V.L. Bratman, M.Yu. Glyavin, Yu.K. Kalynov et al., Int. *J. IRMM&THz Waves*, 32, 371 (2011)

[14] E.A. Nanni, A.B. Barnes, R.G. Griffin, R.J. Temkin, *IEEE Trans. THz Sci. & Technol*, 1, 145 (2011)

[15] J.H. Booske, R.J. Dobbs, C.D. Joye et al., IEEE Trans. *Terahertz Sci. & Technol*., 1, 54 (2011)

[16] T. Idehara, S. Sabchevski, Int. J. *IRMM&THz Waves*, 33, online first (2012)

[17] N.I. Zaytsev, T.B. Pankratova, M.I. Petelin, and V.A. Flyagin, Radio Eng. *Electron Phys*., 19, 103 (1974)

[18] V. Flyagin, A. Luchinin, G. Nusinovich, Int. J. *IRMM Waves*, 4, 629 (1983).

[19] I.I. Antakov, V.A. Gintzburg, L.I. Zagryadskaya, L.V. Nikoleav, Electronnaya Tekhnika, Ser. *Electronica SVCh* (in Russian), 8, 20 (1975)

[20] V.E.Zapevalov, V.I.Kurbatov, O.V.Malygin et al., *USSR Patents,* No.786677, 1980; No. 897039, 1981

[21] S. Spira-Hakkarainen, K.E. Kreischer, R.J. Temkin, *IEEE Trans. Plasma Sci*., 18, 334 (1990)

[22] C.D. Joye, R.G. Griffin, M.K. Hornstein et al. *IEEE Trans. Plasma Sci*., 34, 518 (2006)

[23] P.P. Woskov, V.S. Bajaj, M.K. Hornstein et al., *IEEE Trans. Microw. Theory Techn*., 53, 1863 (2005)

[24] M.K. Hornstein, V.S. Bajaj, R.G. Griffin, R.J. Temkin, *IEEE Trans. Plasma Sci.*, 35, 27 (2007)

[25] M.K. Hornstein, V.S. Bajaj, R.G. Griffin et al., *IEEE Trans. Electron Devices*, 52, 798 (2005)

[26] T. H. Chang, T. Idehara, I. Ogawa et al., *J. Appl. Phys*. 105, 063304 (2009)

[27] V.L. Bratman, M.A. Moiseev, Izv,. *VUZov Radiophisika* (in Russian), 18, 1045 (1975)

[28] T. Idehara, I. Ogawa, S. Mitsudo et al., *IEEE Trans. Plasma Sci*., 27, 340 (1999)

[29] G.F. Brand, Z. Chen, N.G. Douglas et al., *Int. J. Electron*., 57, 863 (1984)

[30] T. Idehara, H. Tsuchiya, O. Watanabe et al., *Int. J. IRMM Waves*, 27, 319 (2006)

[31] M.Yu. Glyavin, A.G. Luchinin, G.Yu. Golubiatnikov, *Phys. Rev. Lett*., 100, 015101, (2008)

[32] G.S. Nusinovich, R. Pu, T.M. Antonsen et al., *Int. J. IRMM&THz Waves*, 32, 380 (2011)

[33] G.S. Nusinovich, Abstracts of the 4th Int. Workshop on Far-Infrared Technologies (IW-FIRT 2012), Fukui, Japan, 7p-3 (2012)

[34] V.L. Bratman, Yu.K. Kalynov, V.N. Manuilov, *Phys. Rev. Lett*. 102, 245101 (2009)

[35] V.L. Bratman, V.G. Zorin, Yu.K. Kalynov et al., *Phys. Plasmas* 18, 083507 (2011)

[36] M. Read, L. Ives, J. Neilson, G. Nusinovich, IEEE Int. Vacuum Electronics Conf. IVEC '07, 347 (2007)

[37] Y. Yang, W. Fu, X. Yuan et al., *Book of Abstracts the 3rd Shenzhen Int. Conf. on Advanced Science & Thechnology*, Shenzhen, China, 46, (2011)

[38] V.E. Zapevalov, V.K. Lygin, O.V. Malygin et al., *Radiophysics & Quantum Electr*., 50, 420 (2007)

[39] J.C. Mudiganti, T. Idehara, Y. Tatematsu et al., Proceedings of 36th Int. Conf. on IRMMW-THz 2011, Houston, TX, USA, 10.1109/irmmw-THz.2011.6105136 (2011)

[40] http://www.bruker-biospin.com/dnp-dir.html

[41] N. Zavolsky, V. Zapevalov, O. Malygin, M. Moiseev, A. Sedov, *Radiophysics and Quantum Electr*., 52, 379 (2009)

[42] M. Glyavin, A. Luchinin, M. Morozkin. Proceedings of the 8 Int. Workshop Strong Microwaves and Terahertz Waves: Sources and Applications, *N.Novgorod*, 107 (2011)

[43] K. Sakamoto, Abstracts of the 4th Int. Workshop on Far-Infrared Technologies (IW-FIRT 2012), Fukui, Japan, 7a-3 (2012)

[44] P. Krivosheev, V. Lygin, V. Manuilov, Sh. Tsimring, Int. *J. IRMM Waves*, 22, 1119 (2001)

[45] A. Goldenberg, M. Glyavin, N. Zavolsky, V. *Manuilov Radiophysics & Quantum Electr.*, 48, 741 (2005)

[46] http://elcut.ru/

[47] N. Ginzburg, I. Zotova, A. Sergeev et al., *Phys. Rev. Lett*. 108 (2012).