NEWSLETTER

of the International Consortium "Development of High-Power Terahertz Science & Technology"

October 2020 № 16

CONTENT

EDITORIAL: HOW TO CONTRIBUTE TO THE NEWSLETTER

Dear Reader,

We are inviting contributions to the following rubrics:

- Research highlights (annotations) presenting the projects pursued by the members of the Consortium.
- Short regular and invited papers.
- Proposals for collaborative research work.
- News from the participating institutions.
- Information about conferences, symposia, workshops, seminars.
- Programs and frameworks for an exchange of visits and mobility of researchers. Job opportunities (especially for young researchers, e.g. postdoctoral positions, specializations, internships).
- Annotations of books, conference proceedings, software and internet resources. Additions to the list of the recent scientific publications and conference reports at the website of the Consortium (http://fir.ufukui.ac.jp/Website_Consortium/publist.html).
- Information and announcements about awards and nominations.
- Short presentations of laboratories and research groups belonging to the participating institutions.

Please submit your contributions to the Newsletter as well as requests for information to:

Professor Masahiko Tani
Director of FIR UF – Facilitator of the International Consortium
FIR UF
tani@fir.u-fukui.ac.jp

Dr. Svilen Sabchevski
Editor of the website and the Newsletter
Institute of Electronics of the Bulgarian Academy of Sciences
sabch@ie.bas.bg

Optimization of an electron gun shape for a third harmonic 1.2 THz/CW gyrotron

V.N. Manuilov[1,2,3], A.I. Tsvetkov[1,3], I.V. Zotova[1,3], A.E.Fedotov[1,3],S. Mitsudo[3], T. Idehara[3], M.Yu. Glyavin[1,3,*]

[1]*Institute of Applied Physics of the Russian Academy of Sciences (IAP RAS), 46 Ulyanov str., Nizhny Novgorod, 603950 Russia*

[2]*Radiophysical department of Nizhny Novgorod State University, 23 Gagarin av., Nizhny Novgorod, 603950, Russia*

[3]*Research Center for Development of Far-Infrared Region, University of Fukui (FIR FU), Bunkyo 3-9-1, Fukui 910-8507, Japan*

[*]Contributed by the corresponding author M. Glyavin: glyavin@ipfran.ru

Abstract. The design of a magnetron-injection gun (MIG) which is appropriate for a CW 3-rd harmonic gyrotron with a frequency of 1.185 THz and the output power about 100 W, intended for DNP/NMR spectroscopy applications is described. To improve the mode selection, several electron-optical schemes are investigated. The MIG allows using both single-beam and double beam schemes of the gyrotron operation with two different operating modes. Requirements for the electron beam parameters are formulated. The design of the triode MIG forming two generating beams with a quality suitable for a third harmonic operation has been accomplished and optimized. A specific feature of the designed MIG is the possibility to form either two beams or one beam using the same electrodes configuration and different number of emitting rings. The proposed MIG design is insensitive to small misalignment and reasonable manufacturing inaccuracy. A key advantage of the design is that it allows improving the mode selection utilizing an electron beam with increased velocity spread as proposed in this study. It is shown that it is possible to form two beams with practically equal and quite high pitch-factors in all range of operating currents and simultaneously small enough coefficient of reflection from the magnetic mirror despite the large enough value of the velocity spread.

Key words: gyrotron, terahertz range, cyclotron harmonic, mode selection, helical electron beam, double-beam magnetron-injection electron gun, numerical simulation.

1. Introduction

The terahertz frequency range (0.1—10 THz) has a number of specific features that make it very attractive for a wide range of fundamental and applied research in the fields of physics, chemistry, biology and medicine [1–3]. In particular, terahertz waves are promising for diagnostics and spectroscopy of various media, including electron paramagnetic resonance (EPR) and high-resolution nuclear magnetic resonance (NMR) methods [3]. Unfortunately, the modern sources of coherent THz radiation have serious limits with respect to the output power.

One of the most promising tubes in the terahertz frequency range are the gyrotrons [4 – 6]. In comparison with other sources of THz radiation they have relatively small weight, size, and cost and power sufficient for many of the mentionad applications. Recently the project of a CW gyrotron operating on the third cyclotron harmonic (15 T magnetic field intensity, 1.2 THz frequency with a power about several Watts) on either $TE1_{5,6}$ or $TE_{21,4}$ cavity modes was suggested and optimized [7]. It is based on the utilization of the conventional single-beam gyrotron scheme. However, the transition towards the THz frequency range sharply increases the density of the modes within the cyclotron frequency band.

The excitation of high cyclotron harmonics needs special methods of mode selection for suppression of the fundamental harmonic mode which has a lower starting current. Usually the gyrotrons use electrodynamic (complex cavity) or electronic (multi-beam, axis encircling beam, etc.) methods to improve the mode selection. For the case of high harmonic number excitation the parasitic modes are far from the cut-off frequency. It means that they are travelling waves and are very sensitive to the velocity spread. To suppress the spurious travelling modes, the scheme based on the helical electron beam (HEB) with a high (30 — 40%) oscillatory velocity spread was suggested [8]. It should be noted that an increase in the velocity spread can somewhat worsen the efficiency of the gyrotron. This, however, is not a critical problem for spectroscopy and diagnostic application that require small microwave power.

Another way to ensure single-mode operation with high enough microwave power (which needs high electron beam current) is to use multi-beam schemes [9 – 12]. Recently, in the common proof of principle experiments of Russian and Japanese teams, the efficiency of this approach for the second cyclotron harmonic operation with two generating HEBs was confirmed [13]. This made it possible to obtain power of about 10 W with a frequency of 0.79 THz using a commercially available and relatively inexpensive 15 T superconducting magnet installed in the experimental setup of FIR FU Center. Thus, to increase the reliability of the single-mode operation with such a high frequency it is better to combine both mentioned above approaches and make the universal gun design suitable for both the single-beam or double beam operation with high value of the velocity spread and simultaneously provide a stable electron beam with a high current.

Below the design of the double-beam triode magnetron-injection gun (MIG) forming two generating beams with the quality suitable for microwave generation with the frequency $\omega \approx 3\omega c$ at the third cyclotron harmonic, is suggested and optimized. In contrast to the traditional design [14], an operation at relatively low voltage (about 20 kV) imposed by the limitations of the currently available high-voltage power supply is analyzed. The specific feature of the gun is that it allows forming either two beams or one beam using the same gun geometry. In the last case, it is provided simply by removing the additional emitter from the cathode surface. The 15 T cryomagnet with a diameter of a warm bore of 52 mm (made by JASTEC, Inc.) installed in University of Fukui (FIR UF Center) will be used. Realization of the stable single-mode CW generation at the third cyclotron harmonic will make it possible to create a unique terahertz radiation source for DNP/NMA spectroscopy and a number of other promising applications.

2. Selection of the injection radii of the electron beams

According to the detailed analysis performed in the previous work [7], the gyrotron can use either $TE_{-15,6}$ or $TE_{21,4}$ modes as the operating ones. The coupling factors for such modes are presented in Fig. 1.

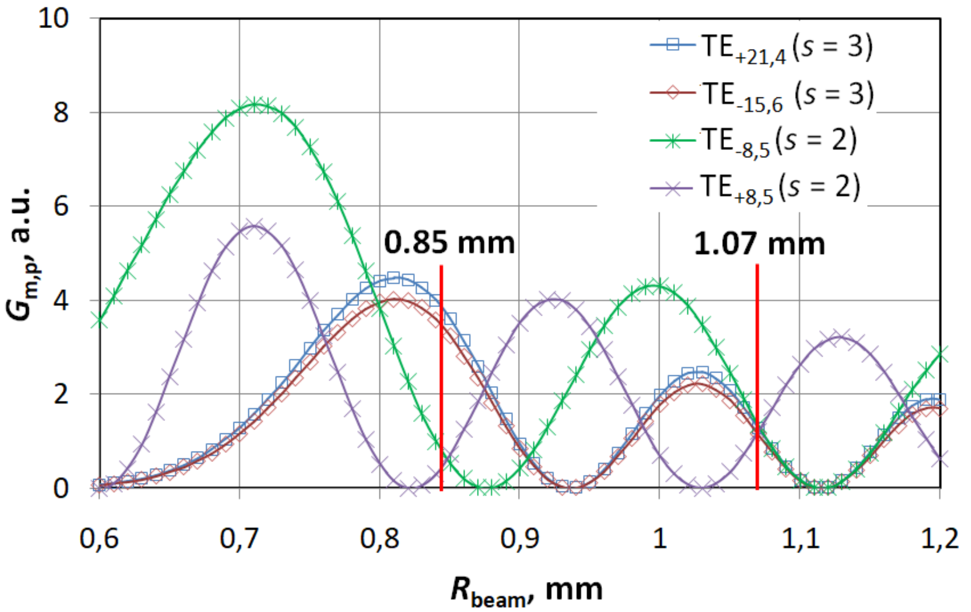

Fig. 1. Coupling factors of the electron beam to the eigenmodes of a cylindrical cavity vs. the electron beam injection radius R_{beam}: $TE_{+21,4}$ (harmonic number s = 3), $TE_{-15,6}$ (s = 3), $TE_{\pm 8,5}$ (s = 2). The cavity radius R_{cavity} is equal to 1.488 mm.

Below, the two versions of a gyrotron are preliminary considered: a conventional ***single-beam*** gyrotron and a ***double-beam*** gyrotron. In the first case, for the injection radius of 0.85 mm, the coupling factor for both operating modes is significantly higher than that for the parasitic ones $TE_{\pm 8,5}$. In the second case, there is also an external HEB with a radius $R_{beam} = 1.07$ mm. This beam has a fairly strong coupling to the parasitic mode, however, its use together with the main internal HEB does not violate the selective excitation of the operating mode (at a reasonable value of the current of this beam) and makes it possible to increase the total current, allowing increasing the output power of the tube.

3. Evaluation of the admissible spread of the electron beam injection radii.

One of the parameters that must be known before starting the design of the MIG is the spread of the guiding centers in the HEB. It defines, to some extent, the electron beam current and possibility to manufacture the emitter ring with a good enough accuracy. We estimated the minimum values of the starting currents in $I_{st\ min}(H)$ curve, where H is the intensity of the magnetic field for the operating mode $TE_{15,6}$, and for the main parasitic mode $TE_{8,5}$ as a function of the thickness ΔR_{beam} of the electron beam. In these calculations, we considered the case of asingle HEB with a radius $R_{beam} = 0.85$ mm.

For the simplest model with a fixed longitudinal structure of the microwave field $f(z) = \sin(\pi z/L)$ (where L is the effective length of the gyrotron cavity), in case when the electron beam has a finite thickness ΔR_{beam}, the starting current can be calculated using a generalization of the well-known formula [5,15]:

$$I_{st}\chi(\theta)\cdot\frac{1}{\Delta R_{beam}}\cdot\int_{R_{beam}-\Delta R_{beam}/2}^{R_{beam}+\Delta R_{beam}/2} G_{m,p}(R)dR = 1,$$

$$\chi(\theta) = \frac{eQL\pi^2\beta_{\perp 0}^{2s-2}}{mc^3\gamma_0\lambda\beta_{\|0}^2}\cdot\left(\frac{s^s}{2^s s!}\right)^2\left(-s-\mu\frac{d}{d\theta}\right)\frac{1+\cos\theta}{[1-(\theta/\pi)^2]^2},$$

$$I_{st\ \min}(\Delta R_{beam}) = \min_H I_{st}(H),$$

where $\theta = (\omega - s\omega_c)L/v_{\|}$ is the transit angle, $\omega_c = eH_0/mc\gamma_0$ is the unperturbed cyclotron frequency, $\gamma_0 = 1 + U_0[\mathrm{kV}]/511$ is the relativistic Lorentz factor, U_0 is the accelerating voltage, Q is the quality factor of the gyrotron cavity, $\beta_{\perp,\|} = v_{\perp,\|}/c$ are the normalized transverse and longitudinal velocities, $\mu = \pi g\beta_{\perp 0}L/\lambda$ is the normalized interaction length, and λ being the radiation wavelength.

The results of the calculation are shown in Fig. 2.

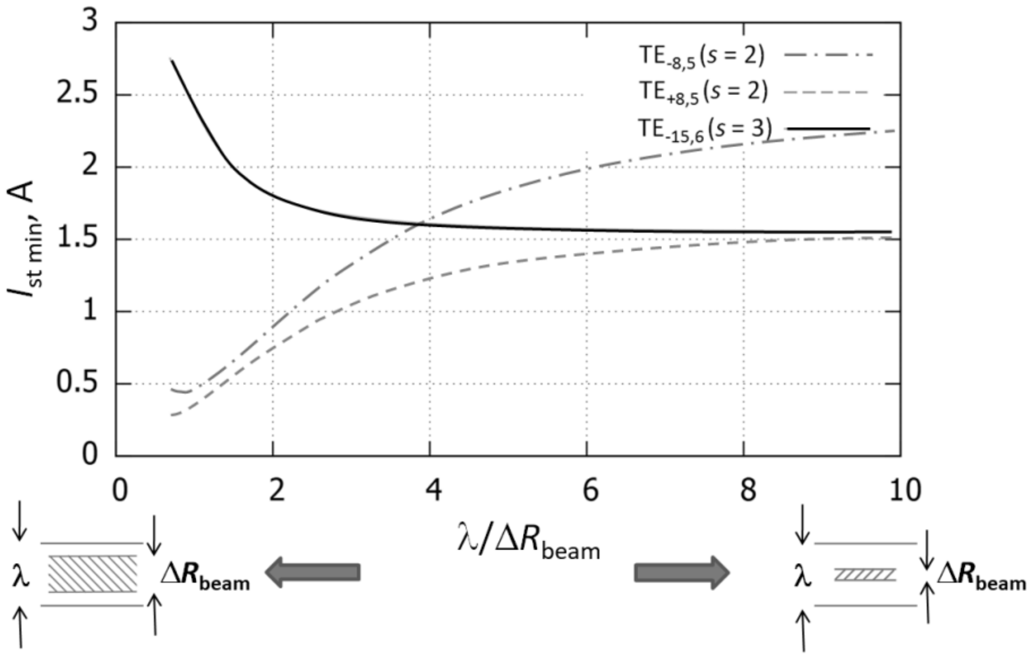

Fig. 2. Minimum value of the starting current $I_{st\ min}$ as a function of the thickness of the electron beam for operating mode $TE_{-15,6}$ and for the parasitic one $TE_{8,5}$, expressed in wavelengths $\lambda/\Delta R_{beam}$.The same value of $\lambda/\Delta R_{beam}$ corresponds to the different values of the magnetic field strength.

With an increase in the HEB thickness, the minimum value of the starting current for the spurious $TE_{8,5}$ modes dramatically decreases (dashed and dash-dotted lines in the figure), and simultaneously, the starting current of the operating one $TE_{-15,6}$ rapidly increases (Fig. 2). Thus, it seems reasonable to choose a beam thickness of about $\lambda/5$ accepting a compromise: on the one hand, a further decrease in the beam thickness does not significantly improve the situation; on the other hand, this value seems realistic from the point of view of the implementation of the electron-optical system.

4. Preliminary adiabatic estimations of the MIG parameters

The gyrotron is based on the same magnetic system as in the project of 0.79 THz double-beam gyrotron at the second cyclotron harmonic [16]. To ensure high coupling of the two beams with the RF field and good enough gyrotron efficiency the following HEBs parameters were chosen: $R_{in} = 0.854$ mm (0.85 mm), $R_{ext} = 1.065$ mm (1.07 mm), $g_{in} = g_{ext} = 1.3$, $\delta v_{\perp in} = \delta v_{\perp ext} \sim 30 – 40\%$, I_{in} , $I_{ext} \geq 0.8$ A. Here the indexes “in” and “ext” correspond to the internal and external beams, respectively and the values in brackets correspond to the $TE_{21,4}$ mode. The spreads of the guiding centers ΔR_{in}, ΔR_{ext} should be less than $\lambda/5$. Here R_{in}, R_{ext} are partial beams radii, g_{in}, g_{ext} – pitch-factors, ΔR_{in}, ΔR_{ext} – spread of the guiding centers, I_{in}, I_{ext} – currents of the beams.

The specified values of injection radii for both operating modes are very close: the difference in corresponding injection radius is less than $\lambda/50$, i.e. 10 times smaller than the admissible value of the guiding centers spread. This allows to design an universal scheme of the double-beam MIG suitable for utilizing in the same gyrotron operating at both specified above modes simply by substituting the corresponding cavity inside the tube (to keep the frequency value of about 1.185 THz for operating mode $TE_{21,4}$ the cavity radii must be equal to 1.492 mm).

A relatively low [17] value of an accelerating (cathode) voltage U_0 should be preferred in order to simplify the gyrotron power supply system. On the other hand, to satisfy the cyclotron resonance condition:

$$\omega \approx 3\omega_c = 3 \cdot \frac{2\pi \cdot 28}{\gamma} \cdot H[\mathrm{T}]$$

for a fixed maximum value of the magnetic field intensity H which is not higher than 15 T we need to limit the value of the accelerating potential to approximately 32 kV. Hence, below we consider a version of the beam-shaping system with a total accelerating voltage of 30 kV and maximum beam current of 3 A (total in two HEBs), which are estimated to guarantee power of about a hundred watts at least. For a more flexible control of the parameters of the partial HEBs, we considered a triode scheme of the MIG with an anode voltage $U_a \approx 12$ kV.

Preliminary analytical estimation of the electric regime and the MIG dimensions was performed based on the adiabatic theory of HEB formation system [12]. The laminar electron beam was suggested, so the magnetic-field line to the emitter angle φ must be $\geq 25°$. The initial gyrotron parameters, which were further used for analytical estimations, are summarized in Table1, whereas the preliminary data of MIG estimations are presented in Table 2.

Table 1.Gyrotron parameters in the interaction space.

Wavelength λ	0.250 mm
Operating magnetic field B_o	14.9 T
Accelerating voltage U_o	30 kV
First-anode potential U_a	12 kV
Beam radii in the cavity R_{ext} (external beam) and R_{in} (internal beam) for $TE_{-15,6}$ mode:	1.065 mm, 0.854 mm
and for $TE_{21,4}$ mode:	1.070 mm, 0.850 mm
Operating beam currents I_{ext} and I_{in}	1.7 A , 1.3 A
Pitch factors g_1 and g_2	1.3, 1.3
Magnetic-field line to emitter surface angle φ	≥ 25°

Table 2.Basic design parameters of the beam shaping system.

Cathode electric field E_c	2.36 kV/mm
Spread of the guiding centers in the cavity, ΔR_o (for both beams)	$\lambda/5$
Emitter width L (for each beam)	1.0 mm
Current density j_c (for both beams)	3.0 A/cm^2
Ratio t_j of the beam current to the Langmuir current (for both beams)	0.25
Magnetic field compression	
α (external and internal beams)	71.4, 69.1
Emitter inclination ψ to the axis (external beam)	30°
Cathode radius R_{c2} (external beam)	9.0 mm
Anode radius R_{a2} (external beam)	14.6 mm
Emitter inclination ψ to the axis (internal beam)	25°
Cathode radius R_{c1} (internal beam)	7.1 mm
Anode radius R_{a1} (internal beam)	13.5 mm

It is important to note that the chosen emitter width (1 mm for both beams) satisfies the mentioned two requirements. On the one hand, such width allows to manufacture the emitter ring using the existing technology (manufacturing of smaller ring is much more complicated task). On the other hand, it corresponds to the restriction imposed by the admissible values of the spreads of the guiding centers in the cavity.

5. Results of the electron trajectory analysis of a double-beam MIG

Second step of the MIG optimization is, as usual, the numerical simulation of the beam properties and optimization of the gun shape.

To simplify the future manufacturing of the electron gun and gyrotron itself and to make it cheaper, the distance from the gun to the cavity was kept close to the distance (570 mm) in the previous version of the double-beam gyrotron [16] operated on the second cyclotron harmonic. Besides, the shape of the second anode was kept the same.

The optimization was done using two-dimensional software EPOS [18]. The final MIG geometry is shown in Figure 3. The first anode is parallel to the tube axis. The beams parameters calculated according to the model without the initial velocity distribution (such model usually is used for the first step of the optimization) are shown in Table 3. Both beams have very close pitch-factors and smooth dependence of their properties on the operating current.

Table 3. Calculated beams parameters in the nominal regime for an anode voltage $U_a = 11.73$ kV

internal beam				external beam			
jk, A/cm^2	I, A	g	$\delta v_\perp$	jk, A/cm^2	I, A	g	$\delta v_\perp$
1.0	0.44	1.46	0.03	1.0	0.56	1.44	0.04
1.5	0.65	1.40	0.04	1.5	0.84	1.39	0.05
2.0	0.87	1.34	0.05	2.0	1.12	1.34	0.07
3	1.31	1.24	0.08	3	1.68	1.24	0.10

The calculations show also that the velocity spread $\delta v_\perp$ practically does not depend on any kind of the gun geometry deviation caused by system misalignment or thermal deformation of the electrodes for both the internal and external electron beams: it varies by no more than ±(0.3 – 1.0)%, while the pitch factor varies by no more than ±0.12 when the longitudinal shift of the magnetic system in the interval ±2 mm occurs. The sensitivity of the pitch-factor to the radial shift of the first anode is significantly higher, especially for the external beam due to the rather small anode-cathode distance and can reach ±0.3. The latter effect, however, can easily be counterbalanced by small variations in the anode potential U_a. Due to the cylindrical form of the first anode the gun is not sensitive to the longitudinal shift of the first anode.

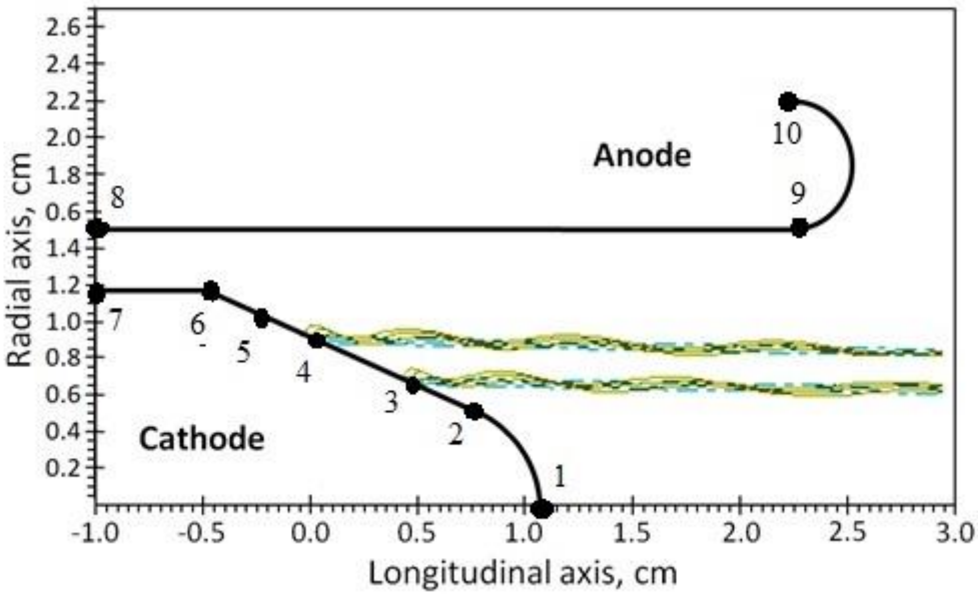

Fig.3. Shape of the electrodes and trajectories of the electrons in the double-beam MIG at the first anode region. The anode potential is 11.73 kV.

The key points of the optimized MIG geometry (Fig.3) are given in table 4, where Z indicates the distance from the center of the external emitter, R – radial position.

Table 4. Position of the key points of the MIG shape

Point number	**1**	**2**	**3**	**4**	**5**
Z, mm	1.066	0.723	0.426	0	-0.31
R, mm	0	0.562	0.689	0.899	0.915
Point number	**6**	**7**	**8**	**9**	**10**
Z, mm	-0.431	-1.0	-1	2.172	2.172
R, mm	1.158	1.17	1.5	1.5	2.3

The final stage of numerical simulation requires a more sophisticated physical model [18-20] which takes into account such important factors as the thermal velocities distribution and the emitter roughness that lead to a significant increase in the velocity spread [21]. Besides, the values of the velocity spread specified in Table 3 are not enough to suppress the spurious modes at the fundamental cyclotron harmonic [8]. For this a spread $\delta v_\perp$ of about 30–40% is needed. Such values may be ensured by the corresponding manufacturing of an emitter with the prescribed emitter roughness r_0 (Fig.4). The velocity spread increases with the emitter surface roughness (the corresponding formula is given in [12, 20]) and for the average roughness heights r_0 = 10 and 20 microns the velocity spread is 27% and 39%, respectively. The specified values of r_0 approximately correspond to the maximum and the minimum admissible values of velocity spread. Therefore, in the used numerical simulation procedure [18] the width of the initial azimuthal velocity distribution function $f(v_{\theta 0})$ was chosen to provide the specified values of velocity spread for low currents of the electron beams (I_{in}, $I_{ext} \to 0$).

The used procedure [18] allowes to find the velocity distribution function in the cavity $F(v_\perp)=dI/dv_\perp$ and thus to calculate the coefficient K_R of reflection from a magnetic mirror for each beam in the operating regime. According to the results of the numerical simulation of HEBs with a high pitch-factor [22], in order to avoid the beam instabilities, it is necessary to provide K_R less than 2 – 3%. For emitter roughness of 20 microns the reflection coefficient is too high (5 – 6%) for any current of both beams. Concurrently, for a roughness of 10 microns in the operating regime with a current density of 3 A/cm^2, the coefficient K_R is small enough (1 –

1.5%) to avoid the beam instability. Thus, one can make the conclusion that the manufacturing technique providing the emitter roughness of 10 microns is quite suitable for meeting the two requirements – rather high pitch-factor and simultaneously large enough velocity spread and a small reflection coefficient. The value of K_R can be decreased 2 – 3 times by turning to smaller pitch-factors in both beams close to 1.2.

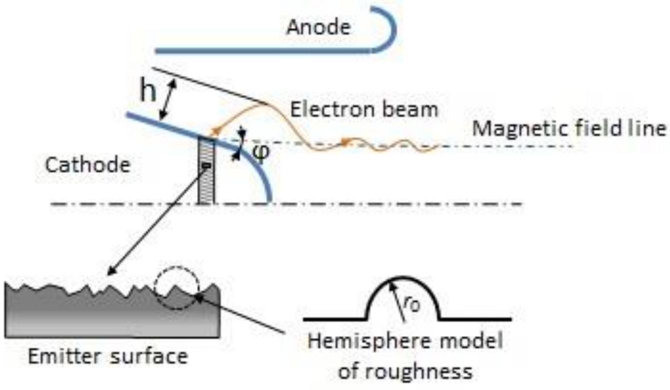

Fig. 4. Electron beam trajectory near the cathode surface and main parameters for estimation of the velocity spread caused by the surface roughness.

The calculations show that increasing currents in each beam shifts the function $F(v_\perp)$ simply toward smaller oscillatory velocities, remaining almost Gaussian for both the internal and external beams. This indicates that stable HEBs are formed in the operating regimes of the MIG.

6. Conclusion

The design of the double-beam electron gun capable to provide the required beams parameters for both operating modes $TE_{-15,6}$ and $TE_{21,4}$ for the developed 1.2 THz CW gyrotron is proposed. Both analytical estimations of the MIG shape and further numerical optimization of its geometry were performed. The sensitivity of the gun to the shift of the gun in the magnetic field and small variations of the anode shape and anode potential are investigated. Special attention was paid to the problem of electrons reflected from the magnetic mirror caused by the emitter roughness. It is shown that the technique providing emitter roughness of about 10 microns is quite suitable to ensure both small reflection coefficient from the magnetic mirror and large enough pitch-factor. The designed gun can provide appropriate parameters for a CW operation of both HEBs. Additionally, the gun design allows to operate it in both single-beam and double-beam versions simply by removing or installing additional emitter on the cathode surface and exciting either $TE_{-15,6}$ or $TE_{21,4}$ modes (to keep the frequency when changing the operating mode it is necessary to replace the cavity with the one with a suitable radius). As a result, it is possible to realize even 4 versions of the gyrotrons having minimal, cheap and simple differences in its design. Such tube has essentially higher flexibility to realize the output power about several tens of watts at least in CW regime with an extremely high frequency close to 1.2 THz. The implementation of the presented project will make it possible to create a unique source for DNP/NMR spectroscopy and a lot of other promising applications.

Acknowledgments

This work supported by RSF grant 19-12-00141.

References:

1. J.H. Booske, “Plasma physics and related challenges of millimeter-wave-to-terahertz and high power microwave generation,” Phys. Plasmas, vol. 15 (2008) 055502. DOI: 10.1063/1.2838240.
2. V.L. Bratman, A.G. Litvak, E.V. Suvorov, "Mastering the terahertz domain: sources and applications," Physics-Uspekhi, vol. 54 (2011) 837. DOI: 10.3367/UFNe.0181.201108e.0867.
3. R.G. Griffin, T.M. Swager, R.J. Temkin, “High frequency dynamic nuclear polarization: New directions for the 21st century,” Journal of Magnetic Resonance, vol. 306 (2019) 128-133. DOI: 10.1016/j.jmr.2019.07.019.

4. A.V. Gaponov, M.I. Petelin, V.K. Yulpatov. Radiophys. Quantum Electron. (1967). DOI: 10.1007/BF01031607.
5. G.S. Nusinovich, Introduction to the Physics of Gyrotrons. Baltimore and London: The Johns Hopkins University Press (2004). DOI: 10.1353/book.62236.
6. N. Kumar, U. Singh, A. Bera, A.K. Sinha, "A review on the sub-THz/THz gyrotrons," Infrared Physics & Technology, vol. 76 (2016) 38-51. DOI: 10.1016/j.infrared.2016.01.015.
7. V.N. Manuilov, T. Idehara, S. Mitsudo, O. Dumbrajs, M.Yu. Glyavin, A.I. Tsvetkov, I.V. Bandurkin, A.E. Fedotov, "Third harmonic CW gyrotron with operating frequency 1.2 THz for a DNP/NMA spectroscopy," 2019 International Vacuum Electronics Conference (IVEC) (2019). DOI: 10.1109/IVEC.2019.8745302.
8. M. Yeddulla, G.S. Nusinovich, T.M. Antonsen, "Start currents in an overmoded gyrotron," Phys. Plasmas, vol. 10 (2003) 4513. DOI: 10.1063/1.1618777.
9. V.E. Zapevalov and S.E. Tsimring, *Radiophysics and Quantum Electronics*, 33(11), pp. 954-990, 1990.
10. G. Bekefi, "Double stream cyclotron maser," Nuclear Instruments&Methods in Physics Research, vol. 318 (1992) 243-246. DOI: 10.1016/0168-9002(92)91060-M.
11. S.G. Liu, X.S. Yuan, W.J. Fu, Y. Yan, Y.X. Zhang, H.F. Li, and R.B.Zhong, "The coaxial gyrotron with two electron beams. I. Linear theory and nonlinear theory," Physics of Plasmas, vol. 14 (2007) 103113. DOI: 10.1063/1.2784766.
12. Sh.E. Tsimring, Electron Beams and Microwave Vacuum Electronics. Hoboken, NJ: John Wiley&Sons. Inc. (2007). DOI: 10.1002/0470053763.
13. T. Idehara, M. Glyavin, A. Kuleshov, S. Sabchevski, V. Manuilov, V. Zaslavsky, I. Zotova, A. Sedov, "A novel THz-band double-beam gyrotron for high-field DNP-NMR spectroscopy," Rev Sci. Instrum., vol. 88 (2017) 094708. DOI: 10.1063/1.4997994.
14. M. Glyavin, A. Luchinin, V. Manuilov, G. Nusinovich, "Design of a Subterahertz, Third-Harmonic, Continuous-Wave Gyrotron," IEEE Transactions on Plasma Science, vol. 36 (2008) 591 - 596. DOI: 10.1109/TPS.2008.917530.
15. O. Dumbrajs, T. Idehara, T. Saito, and Y. Tatematsu, "Calculations of Starting Currents and Frequencies in Frequency-Tunable Gyrotrons," Jpn. J. Appl. Phys., vol. 51 (2012). DOI: 10.1143/JJAP.51.126601.
16. V.N. Manuilov, M.Yu. Glyavin, A.S. Sedov, V.Yu. Zaslavsky, T. Idehara, "Design of a Second Harmonic Double-Beam Continuous Wave Gyrotron with Operating Frequency of 0.79 THz," J. Infrared Millim. Terahertz Waves, vol. 36 (2015) 1164–1175. DOI: 10.1007/s10762-015-0209-x.
17. M.Glyavin, N.Zavolsky, A.Sedov, G.Nusinovich, "Low-voltage gyrotrons," Physics of plasmas, vol. 20 (2013) 033103. DOI: 10.1063/1.4791663.
18. P.V. Krivosheev, V.K. Lygin,V.N. Manuilov, Sh.E. Tsimring,.Int. J. Infrared Milli. Waves (2001). DOI: 10.1023/A:1015006230396.
19. V.K. Lygin, "INumerical simulation of intense helical electron beams with the calculation of the velocity distribution functions," nt. J. Infrared Milli. Waves, vol. 16 (1995) 363–376. DOI: 10.1007/BF02096323.
20. U. Singh, N. Kumar, A.K. Sinha, "Magnetron Injection Gun for a Short Pulse, 0.67 THz Gyrotron for Remote Detection of Radioactive Materials," IEEE Transactions on Terahertz Science and Technology, vol. 4 (2014) 509–514. DOI:10.1109/tthz.2014.2327374.
21. Sh. E. Tsimring, "On the spread of velocities in helical electron beams," Radiophys. Quantum Electron., vol. 15 (1972) 952–961 . DOI: 10.1007/BF01030951.
22. V.N. Manuilov, "Numerical simulation of low-frequency oscillations of the space charge and potential in the electron-optical system of a gyrotron," Radiophys. Quantum Electron. Vol. 49 (2006) pages786–792. DOI: 10.1007/s11141-006-0113-2.

Design of a Third-Harmonic 1.2 THz/CW Gyrotron with an Intentionally Increased Velocity Spread of Electrons

I.Bandurkin[1,2], A.Fedotov[1.2], M. Glyavin[1,*], T. Idehara[2], A. Malkin[1], V. Manuilov[1,2,3], S.Mitsudo[2], A. Sergeev[1], S.Sabchevski[2,4], A. Tsvetkov[1,2], V. Zaslavsky[1,3] , I. Zotova[1,2]

[1]*Institute of Applied Physics of the Russian Academy of Sciences (IAP RAS*

[2]*Research Center for Development of Far-Infrared Region,*
University of Fukui (FIR FU),

[3]*Radiophysical Department of Nizhny Novgorod State University*

[4]*Institute of Electronics of the Bulgarian Academy of Science (IRE BAS)*

[*]Contributed by the corresponding author M. Glyavin: glyavin@ipfran.ru

Abstract. In this paper, the concept of a CW 1.185 THz (wavelength about 250 μm) gyrotron with an output power of several watts, intended for DNP/NMR spectroscopy applications is presented. For a 15 T magnetic field provided by a commercially available cryomagnet, the required frequency can be achieved by operating at the 3rd cyclotron harmonic. Under conditions of extreme density of the mode spectrum, we propose using interaction with an electron beam intentionally formed with a high (up to 40%) velocity spread as a selection mechanism. This ensures suppression of the most dangerous parasitic traveling modes at the first and the second cyclotron harmonics, which are very sensitive to the velocity spread. The main parameters of the gyrotron are determined both using the start currents analysis and within the framework of a non-stationary self-consistent physical model. The feasibility of the single-mode 3rd harmonic generation under conditions of mode competition is verified based on 3D PIC (particle-in-cell) simulations. The design of the triode MIG forming two generating beams with a quality suitable for third harmonic operation is suggested and optimized. The specific feature of the MIG is the possibility to form either two beams or one beam using the same electrode geometry and different number of emitting rings. The proposed MIG is not sensitive to small misalignment and reasonable manufacturing errors. It is shown that it is possible to form two beams with practically equal and quite high pitch-factors in all range of operating currents and simultaneously small enough coefficient of reflection from the magnetic mirror despite the large enough value of the velocity spread.

***Keywords* — gyrotron; electron beam; THz radiation, harmonic excitation, velocity spread, mode selection, magnetron-injection electron gun, numerical simulation.**

1. Introduction

Nowadays, sources of terahertz radiation are in great demand due to their numerous scientific and technological applications in physics, chemistry, biology, medicine, etc. Over the last few years, there has been a significant progress in the development of short-wavelength gyrotrons operating at frequencies of 0.4-1 THz [1-5]. The maximum radiation power was achieved in fundamental-harmonic gyrotrons with pulsed magnetic fields [1-3]. At the same time, for continuous-wave (CW) generation in the THz band, operation at higher-order harmonics of the cyclotron frequency is inevitable due to the limitation to magnetic field intensity provided by the available state-of-the-art cryomagnets. However, high harmonic operation leads to complication of the problem of mode selection in gyrotron cavities, which in the THz band should be significantly oversized.

Currently, a number of methods aimed to improve the situation are under development, which include multi-beam gyrotrons [4], interaction with axis-encircling rotating electron beams in the so-called large-orbit gyrotrons (LOGs) [5,6], the use of complex-profile [7-9] or coaxial cavities [10,11], etc. At the same time, the obvious disadvantages of these methods are caused by difficulties in manufacturing of sophisticated resonators and/or electron guns. For example, for LOGs, the formation of axis-encircling electron beams requires the use of specific cusp magnetic systems. Partly for this reason, operation at the 3rd cyclotron harmonic in LOGs with the frequency about 1 THz was realized in compact pulse coils, while CW operation with modern cryomagnets has been obtained only at the frequencies lower than 0.4 THz [5].

At the same time, the natural mechanism of parasitic mode suppression in the conventional gyrotrons is associated with the influence of the electron velocity spread which strongly affects the resonance conditions of the spurious travelling modes. However, as is well-known, the large spread deteriorates the gyrotron optimum efficiency significantly even for the near-cutoff modes. Thus, the electron guns are usually designed in such a way as to provide the spread in the orbital velocities not exceeding 15-20%. These values are insufficient for provision of the selective excitation of the 3rd cyclotron harmonic in conditions of an extremely dense mode spectrum, as the starting currents of the spurious modes remain far below that of the operating one (see below). Nevertheless, the situation can be quite different for higher values of the velocity spread, 30 to 40 %; here, besides the significant increase in the starting currents of the spurious 1st and 2nd harmonic traveling modes, the starting current of the operating near-cutoff 3rd harmonic mode is reduced. This latter effect [12-14] can be explained by the influence of “slow” electron fractions with smaller axial velocities which contribute more to the electron susceptibility due to two factors: first, they interact with the cavity field longer; second, these particles have higher transverse velocity. As a result, for near-cutoff modes, this contribution is larger than the negative contribution of the electrons with larger axial velocities and thus the total susceptibility is increased.

Therefore, using an electron beam with a large velocity spread one can provide conditions when the excitation zone of the 3rd harmonic near-cutoff mode is not masked by zones of spurious modes excited at the 1st and the 2nd cyclotron harmonics, assuming these latter modes are traveling. In this paper, we use such an approach for development of a 1.185 THz CW gyrotron intended for spectroscopic applications. In Section II, basic parameters of the gyrotron are determined based on an analysis of the starting currents as well as within the framework of a self-consistent non-stationary multimode model in which the difference in the interaction (transit) time for “slow” and “fast” electron fractions is taken into account. In Section III, the feasibility of single-mode 3rd harmonic generation is verified based on 3D PIC (particle-in-cell) simulations using CST STUDIO SUITE [15].

2. Analysis of the starting currents and estimations of the output Parameters

In designing a gyrotron, the first thing to do is to choose an operating mode based on the parameters of the gyrotron cavity determined by the technological properties of state-of-the-art milling machines. These are capable of manufacturing relatively long (tens of millimeters) cylindrical cavities with diameters of $2R \sim 2.5 \div 3$ mm with a sufficient precision (inaccuracy less than 0.01λ). Since the mode competition problem becomes more severe with an increasing of R, the inner diameter of the cavity was chosen close to the minimum admissible value $2R = 3$ mm. For an operation at a quasi-cutoff frequency ω_c, the condition $\omega_c / c \approx \nu / R$ should be fulfilled, where ν is the eigenvalue of a $TE_{m,q}$ mode of a cylindrical waveguide. Thus, for an operating frequency of 1.2 THz, one should choose a mode with $\nu \approx 37$. The above considerations allow us to propose the $TE_{-15,6}$ mode as an operating one for which the maximum value of the coupling factor is reached for a beam injection radius of 0.84 mm. In this case, the most “dangerous” parasitic modes are, at the 1st cyclotron harmonic, $TE_{6,2}$ and, at the 2nd cyclotron harmonic, $TE_{-3,7}$, $TE_{-1,8}$, $TE_{-8,5}$; among these, only $TE_{-8,5}$ is quasi-cutoff.

Calculations of the starting current were performed within the framework of the single-mode stationary model based on 1D hyperbolic “non-uniform string” equation [16.17] for the field amplitude and averaged over the cyclotron period linearized equations for the motion of the electrons. The distribution of the beam particles over the transverse velocities at the cavity entrance was assumed to be Gaussian with the width at the level e^{-1} taken for the velocity spread value. The operating zones of the indicated modes shown in Fig. 1 were found for the gyrotron cavity length of 15 mm and the following parameters of the driving electron beam: electron energy 30 keV and mean pitch-factor 1.3. One can see that at zero velocity spread (Fig. 1a) and at the velocity spread of 20% typical for conventional gyrotrons (Fig. 1b), there is no chance of selective excitation of the operating 3rd harmonic mode (blue line) with a minimum starting current of 1.5 A, due to the fact that the starting current of the 1st harmonic spurious mode $TE_{6,2}$ (red line) is significantly lower. At the same time, the situation becomes quite different for a sufficiently large velocity spread of 40% (Fig. 1c). In this case, the minimum starting current of the operating $TE_{-15,6}$ mode is reduced to 0.5 A, while the starting current of the most "dangerous" fundamental harmonic mode increases significantly up to 2-2.5 A.

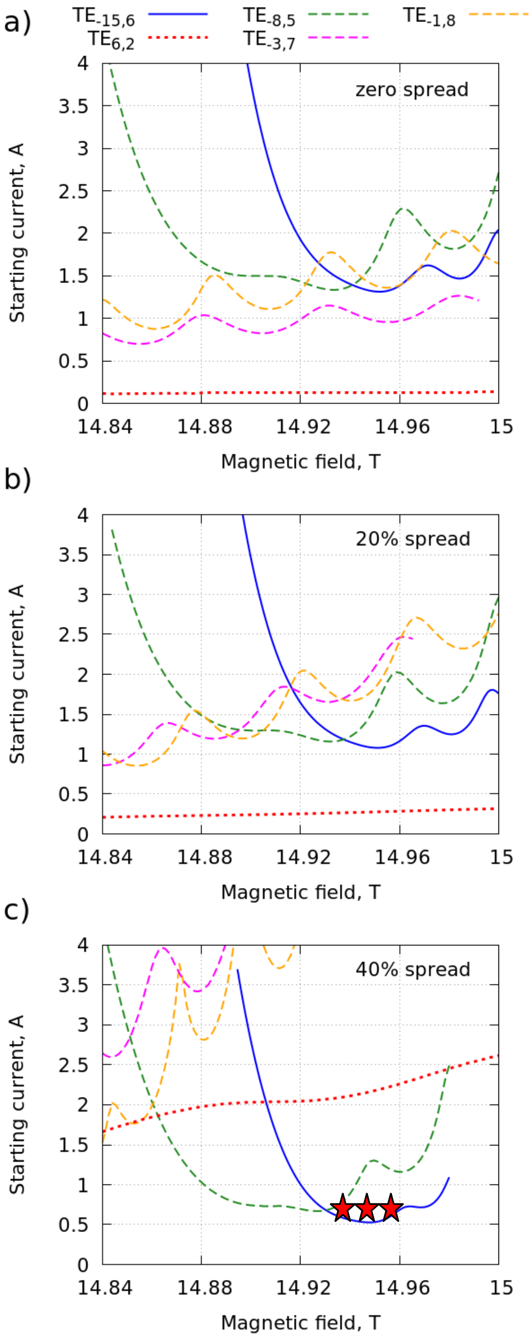

Fig.1 Starting currents of modes interacting at the fundamental (dotted), second (dashed), and third (solid) cyclotron harmonics for the designed 1.2 THz CW gyrotron: (a) – zero velocity spread in the electron beam; (b) – 20% spread, (c) – 40% spread. The red stars show the zone where selective excitation of the operating mode was obtained in 3D PIC simulations.

As mentioned above, this is caused by the influence of "slow" electron fractions with a longer transit time. For the second-harmonic spurious mode the situation is similar: the starting currents of the travelling $TE_{-3,7}$ and $TE_{-1,8}$ modes increase significantly, while the excitation zone of the near-cutoff $TE_{-8,5}$ mode is slightly shifted down as is for the operating mode. Nevertheless, one can see that for magnetic fields 14.93-14.98 T, a zone exists with no competing modes for the 3rd harmonic operating $TE_{-15,6}$ mode. This effect can be observed for at least 10-15% parameter variation (that is, pitch 1.2-1.4 and length of the resonator 15-17 mm).

In the simulations, the following physical model has been used:

$$i\frac{\partial^2 a_n}{\partial Z^2}+s_n\frac{\partial a_n}{\partial \tau}+\left(i\Delta_n+i\delta_n(Z)+\sigma_n\right)a_n=$$
$$=i\frac{I_n}{4\pi^2}\frac{\int_0^{2\pi}e^{i(m_n-s_n)\varphi}\int\alpha(p_0)\left\langle p^s\right\rangle_{\theta_0}dpd\varphi}{\int\beta_{\|}\alpha(p_0)/\bar{\beta}_{\|}\,dp},\qquad(1)$$
$$\frac{\partial p}{\partial Z}+\frac{\bar{\beta}_{\|}}{\beta_{\|}}\frac{\bar{g}^2}{4}\frac{\partial p}{\partial\tau}+\frac{\bar{\beta}_{\|}}{\beta_{\|}}ip\left(|p|^2-|p_0|^2\right)=$$
$$=i\sum_n a_n\frac{\bar{\beta}_{\|}}{\beta_{\|}}\left(p^*\right)^{s_n-1}e^{-i(m_n-s_n)\varphi}.$$

Here, a_n is the normalized amplitude of the n-th mode TE_{m_n,q_n} excited at the cyclotron harmonic with a number s_n, p is the normalized complex transverse momentum of the electrons, $\tau=\omega_g\bar{\beta}_{\perp}^4 t/8\bar{\beta}_{\|}^2$, $Z=\bar{\beta}_{\perp}^2\omega_g z/2\bar{\beta}_{\|}c$, $\bar{\beta}_{\|,\perp}=\bar{v}_{\|,\perp}/c$ are the mean values of the normalized longitudinal and transverse velocities of the electron beam with a velocity spread, $\bar{g}=\bar{\beta}_{\perp}/\bar{\beta}_{\|}$ is the mean pitch-factor, $\Delta_n=8\bar{\beta}_{\|}^2 s_n\left(s_n\omega_g-\bar{\omega}_n^c\right)/\bar{\omega}_n^c\bar{\beta}_{\perp}^4$ is the cyclotron resonance detuning for the n-th mode with a cut-off frequency $\bar{\omega}_n^c$ in the regular part of a smoothly tapered gyrotron cavity, $\omega_g=eB_0/m_e c\gamma$ is an unperturbed relativistic gyro-frequency, $\gamma=1+eU/m_e c^2$ is the relativistic factor, U is the accelerating voltage, m_e is the electron's rest mass,

$$I_n=64\frac{eI_b}{m_e c^3}\frac{\bar{\beta}_{\|}\bar{\beta}_{\perp}^{2(s_n-4)}}{\gamma}s_n^3\left(\frac{s_n^{s_n}}{2^{s_n}s_n!}\right)^2\frac{J_{m_n-s_n}^2(\nu_n R_b)}{\left(\nu_n^2-m_n^2\right)J_{m_n}^2(\nu_n)}.$$

An additional analysis of the possibility of single-mode excitation at the 3rd cyclotron harmonics under the conditions of mode competition is carried out on the basis of a non-linear theory within which the process of electron-wave interaction is described by the following self-consistent system of equations (cf. [18]) are the normalized current parameters, R_b is an injection radius of a tubular electron beam with current I_b, ν_n is the eigenvalue of the n-th mode. Function $\alpha(p_0)$ is defined as an electron transverse velocity distribution function (further assumed to be Gaussian), $\beta_{\|}/\bar{\beta}_{\|}=\sqrt{\bar{g}^2+1-\bar{g}^2|p_0|^2}$, σ_n is the parameter of Ohmic losses proportional to the skin depth, functions $\delta_n(Z)=8\bar{\beta}_{\|}^2\left(\bar{\omega}_n^c-\omega_n^c(Z)\right)/\bar{\beta}_{\perp}^4\bar{\omega}_n^c$ describe the geometrical detunings in a gyrotron cavity with profile $R(z)$, $\omega_n^c(Z)=\nu_n c/R(z)$. Note, that the term $(\bar{\beta}_{\|}\bar{g}^2/4\beta_{\|})\partial p/\partial\tau$ in the motion equations permits us to take into account the finiteness of the particle transit time [19], which is different for different electron fractions of the electron beam with non-zero velocity spread. Thus, based on the developed approach, the influence of "slow" fractions can be directly taken into account using such non-stationary model. For comparison, the previous non-stationary gyrotron theory taking into account the velocity spread (see, for example, [18]) was developed under the assumption that the electron transit time is much shorter than the cavity decay time. Actually, it meant that in the simulations, the transit time was considered to be zero for all electron fractions.

In order to introduce appropriate boundary conditions, we assume that at the input cross section $Z=0$, the electrons are uniformly distributed over the cyclotron rotation phases $p(Z=0)=p_0 e^{i\theta_0}$, $\theta_0\in[0,2\pi)$. For the amplitude of electromagnetic field standard non-reflection boundary conditions can be applied on the edges of the interaction space (cf. [20]):

$$a_n(\tau,Z=0)-\frac{1}{\sqrt{i\pi s_n}}\int_0^{\tau}\frac{e^{-is_n^{-1}\chi_n^0(\tau-\tau')}}{\sqrt{\tau-\tau'}}\left.\frac{\partial a_n(\tau',Z)}{\partial Z}\right|_{Z=0}d\tau'=0,$$
$$a_n(\tau,Z=L)+\frac{1}{\sqrt{i\pi s_n}}\int_0^{\tau}\frac{e^{-is_n^{-1}\chi_n^L(\tau-\tau')}}{\sqrt{\tau-\tau'}}\left.\frac{\partial a_n(\tau',Z)}{\partial Z}\right|_{Z=L}d\tau'=0,\qquad(2)$$

where $L = \bar{\beta}_\perp^2 \omega_H l / 2\bar{\beta}_\parallel c$ is the normalized length of the gyrotron cavity, $\chi_n^0 = \Delta_n + \delta_n(Z=0) + \sigma_n$, $\chi_n^L = \Delta_n + \delta_n(Z=L) + \sigma_n$.

Based on Eqs. (2), we carry out simulations, in which the competition of the operating 3d harmonic $TE_{-15,6}$ mode with the most dangerous modes ($TE_{6,2}$ at the 1st cyclotron harmonic and $TE_{-8,5}$ at the 2nd cyclotron harmonic) is taken into account. The results of the simulations for the beam current of 0.7 A are presented in Fig.2.

One can see that, according to both linear and non-linear analysis, for zero velocity spread, the excitation of the 1st harmonic travelling mode with five axial variations of the field along the gyrotron cavity (Fig.2, left column) takes place (radiation power is 140 W). At the same time, introduction of the large velocity spread allows us to successfully suppress the excitation of both parasitic modes. As a result, we obtain selective single-mode excitation at the 3d cyclotron harmonic with one axial variation of the field (Fig.2, right column). This approach allows us to estimate the output radiation power which, according to the simulations, can reach 10 W.

Note that the starting currents can also be found from Eqs. (1)-(2) by linearization and replacement of $\partial/\partial\tau$ terms with $i\Omega$, where $\Omega = 8\bar{\beta}_\parallel^2 (\omega - s_n\omega_g)/\omega_g \bar{\beta}_\perp^4$. However, in Eq. (1) we used the parabolic dispersion approximation valid near the exact cutoff frequency; thus the starting currents presented in Fig.1 are more accurate as they are found based on exact hyperbolic dispersion equations.

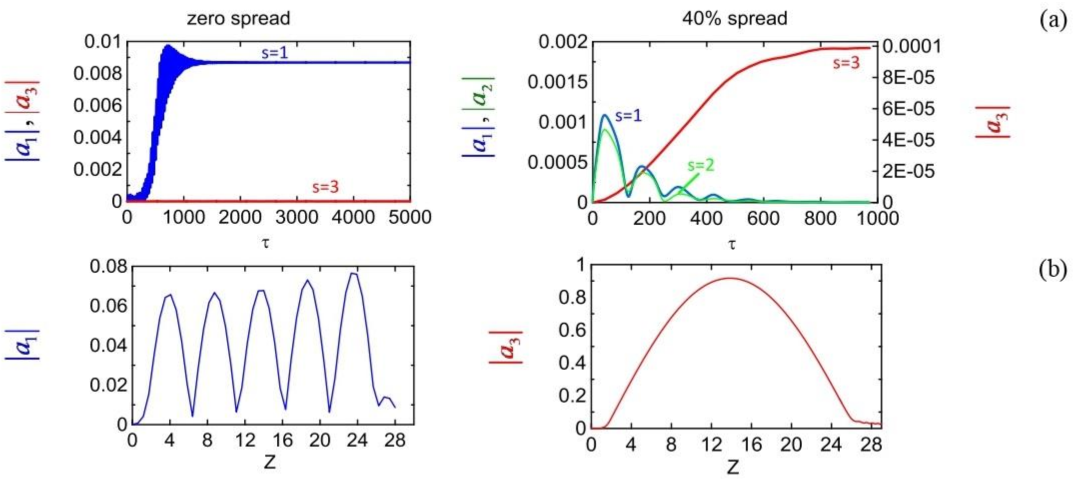

Fig.2 Results of the simulations within the framework of the averaged approach (1) for the operating current of 0.7 A. Oscillations onset (a) and the longitudinal profile of the field amplitude in CW regime (b) for zero velocity spread (left column) and large spread of 40% (right column). (B_0 = 14.92 T)

3. Results of 3D PIC simulations

The obtained results have been confirmed by the 3D PIC simulations performed using CST Studio Suite. Such an approach allows us to take into account the competition of all the modes in the gyrotron cavity. However, for an extremely high operating frequency (over 1 THz) and excitation of the 3d cyclotron harmonic, this requires significant computer resources compared to simulations within the framework of the averaged equations approach (1). For the parameters chosen above, the simulation was run with approximately 7×10^7 hexahedral mesh cells. The total number of macroparticles in the interaction space reached 3×10^6 injected from 128 different injection points. The simulations were carried out using a multiprocessor computer with 16 parallel processors and 2 GPUs. Forty nanosecond long simulation (which is sufficient for the onset of a steady-state regime) required approximately 100 hours of computational time. In general, the performed simulation resembles the one performed in [21]. However, unlike the simulation of gyrotrons at the fundamental harmonic of the gyrofrequency, the study of the interaction processes at higher cyclotron harmonics requires an increase in the accuracy of the calculations. Correct description of a rotating operating mode calls for a substantial increase in the number of cells. In addition, the analysis of gyrotron operation at higher harmonics requires a fairly accurate determination of the oscillatory velocity spread and, accordingly, a significantly larger number of macro-particles.

The rsults of the simulations are presented in Fig.3 and 4. The conductivity of copper walls ~$5.8 \cdot 10^7$ S/m was taken into account for proper calculation of the Ohmic losses. For zero spread, an excitation of the 1st harmonic $TE_{6,2}$ mode is observed (Fig.3). At the same time, for a spread of 40%, selective excitation of $TE_{-15,6}$ mode at the 3rd cyclotron harmonic with operating frequency of 1.185 THz takes place (Fig.4). The output power in PIC simulations is about 6 W, which is in a good agreement with the results obtained within the framework of the averaged approach. Note also that operating regimes with the power of several watts were observed for zone of magnetic fields from 14.93 to 14.96 T, which is close to theoretical prediction (see Fig.1c).

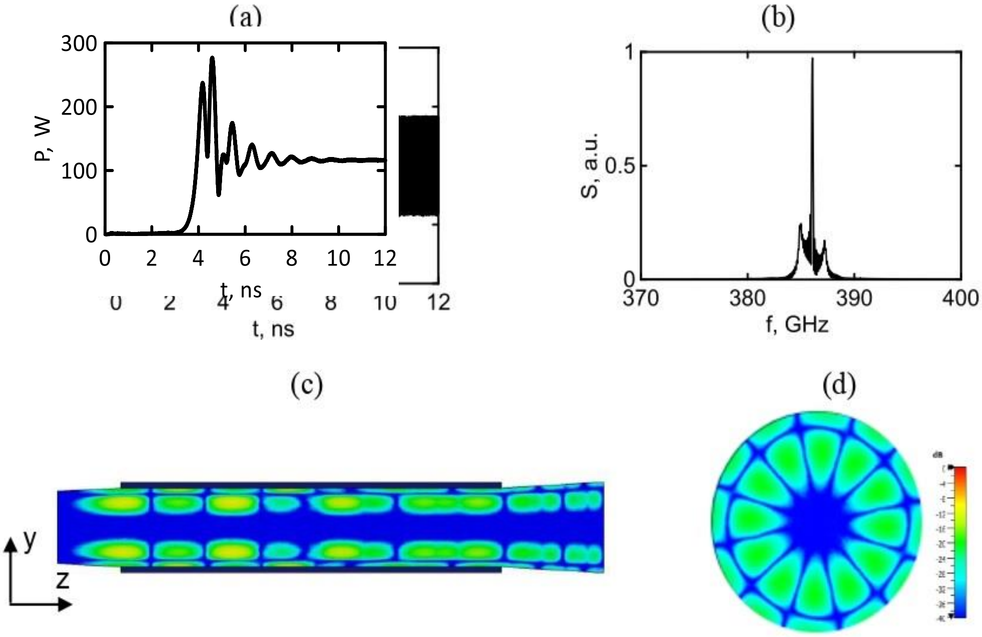

Fig.3 Results of 3D PIC simulations in the case of zero velocity spread: (a) output power vs time; (b) radiation spectrum; (c), (d) axial and transverse field structures corresponding to an excitation of $TE_{6,2}$ mode at the fundamental cyclotron harmonic. (B_0 = 14.94 T, U = 30 kV, I_b = 0.7 A)

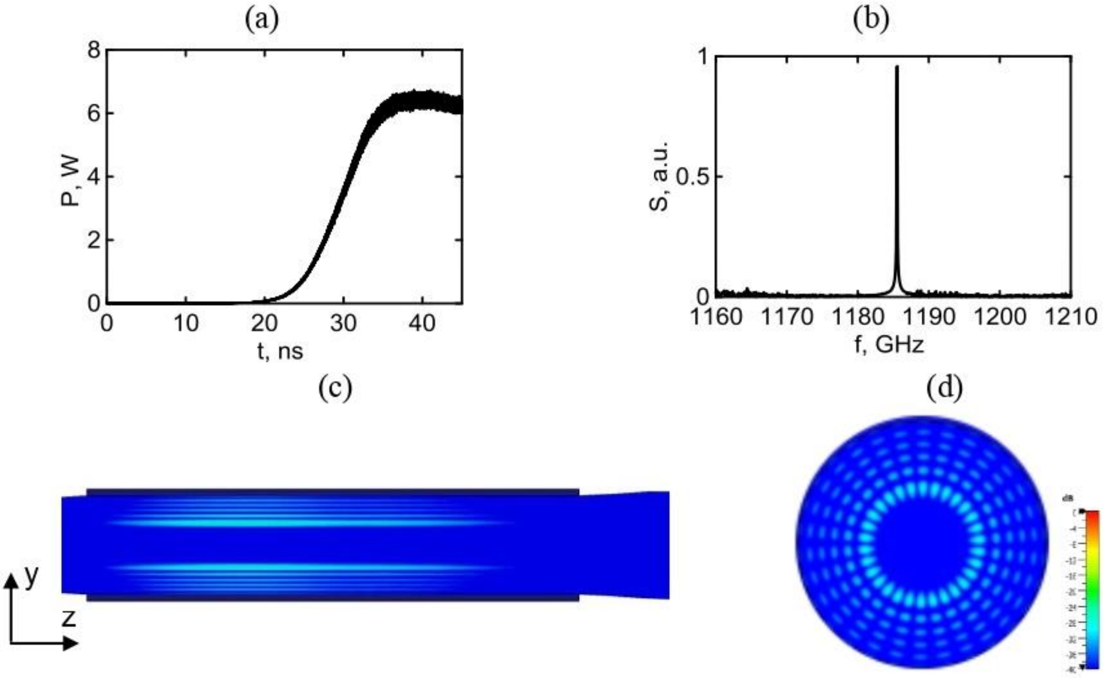

Fig.4 The same as in Fig.3 for velocity spread of 40%, when selective excitation of $TE_{-15,6}$ mode at the 3d cyclotron harmonic takes place. (B_0 = 14.94 T, U = 30 kV, I_b = 0.7 A)

4. Selection of the injection radius of the electron beam

The coupling factors for $TE_{-15,6}$ or $TE_{21,4}$ modes are presented in Figure 5.

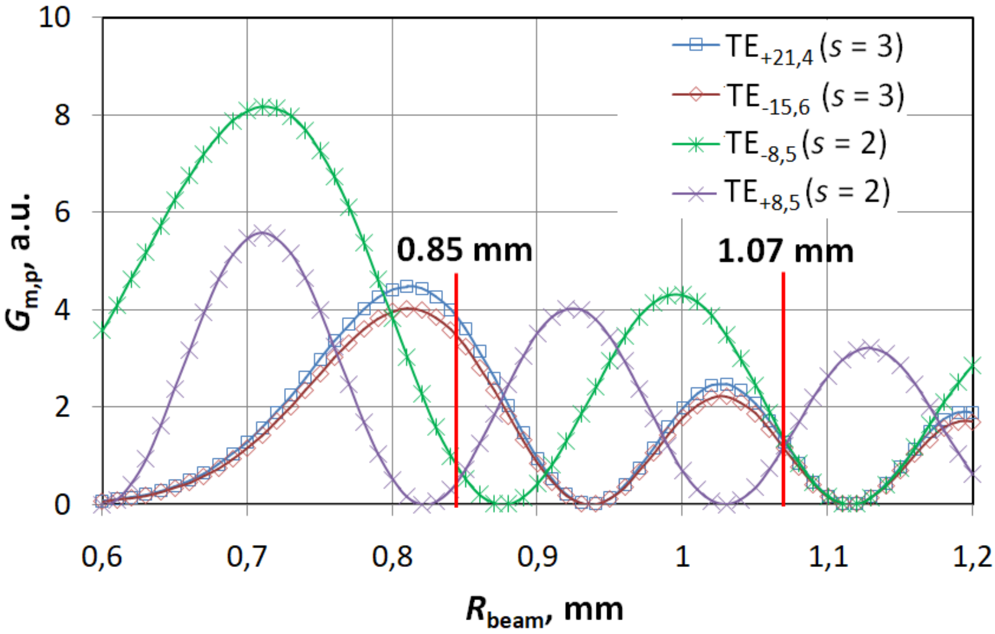

Fig. 5. Coupling of the electron beam to the eigenmodes of a cylindrical cavity vs. the electron beam injection radius R_{beam}: $TE_{+21,4}$ (harmonic number s = 3), $TE_{-15,6}$ (s = 3), $TE_{\pm 8,5}$(s = 2).Cavity radius R_{cavity} is equal to 1.488 mm.

Below, the two versions of a gyrotron are preliminary considered: a conventional ***single-beam*** gyrotron and a ***double-beam*** gyrotron. In the first case, for an injection radius of 0.85 mm, the coupling factor for both operating modes is significantly higher than for the parasitic ones $TE_{\pm 8,5}$. In the second case, there is also the external helical electron beam (HEB) with a radius R_{beam} = 1.07 mm. This beam has a fairly strong coupling to the parasitic mode. However, its usage together with the main internal HEB does not violate the selective excitation of the operating mode (at a reasonable value of the current of this beam) and makes it possible to increase the total current, allowing increasing the output power of the tube.

5. Admissible spread of the electron beam injection

One of the parameters that must be known before starting the design of the MIG is the spread of the guiding centers in the HEB. It defines, to some extent, the electron beam current and possibility to manufacture the emitter ring with good enough accuracy. We estimated the minimum values of the starting currents in $I_{st\,min}$ (B) curve, where B is the intensity of the magnetic field, for one of the operating modes, $TE_{15,6}$, and for the main parasitic mode $TE_{8,5}$ as a function of the thickness ΔR_{beam} of the electron beam. In these calculations, we considered the case of a single HEB with a radius R_{beam} = 0.85 mm.

For the simplest model with a fixed longitudinal structure of the microwave field $f(z) = \sin(\pi z/L)$ (where L is the effective length of the gyrotron cavity), in case when the electron beam has a finite thickness ΔR_{beam}, the starting current can be calculated using a generalization of the well-known formula [17, 22]:

$$I_{st}\chi(\theta)\cdot\frac{1}{\Delta R_{beam}}\cdot\int_{R_{beam}-\Delta R_{beam}/2}^{R_{beam}+\Delta R_{beam}/2} G_{m,p}(R)dR = 1,$$

$$\chi(\theta)=\frac{eQL\pi^2\beta_{\perp 0}^{2s-2}}{mc^3\gamma_0\lambda\beta_{\parallel 0}^2}\cdot\left(\frac{s^s}{2^s s!}\right)^2\left(-s-\mu\frac{d}{d\theta}\right)\frac{1+\cos\theta}{[1-(\theta/\pi)^2]^2},$$

$$I_{st\,\min}(\Delta R_{beam}) = \min_H I_{st}(H),$$

where $\theta = (\omega - s\omega_c)L/v_{\parallel}$ is the transit angle, $\omega_c = eH_0/mc\gamma_0$ is the unperturbed cyclotron frequency, $\gamma_0 = 1 + U_0[\text{kV}]/511$ is the relativistic mass factor, U_0 is the accelerating voltage, Q is the quality factor of the gyrotron cavity, $\beta_{\perp,||} = v_{\perp,||}/c$ are the normalized transverse and longitudinal velocities, $\mu = \pi g \beta_{\perp 0} L/\lambda$ is the normalized interaction length, and λ is the radiation wavelength.

The results of the calculation are shown in Fig. 6.

With an increase in the HEB thickness, the minimum value of the starting current for the spurious $TE_{8,5}$ modes dramatically decreases (dashed and dash-dotted lines in the figure), and simultaneously, the starting current of the operating one $TE_{-15,6}$ rapidly increases (Fig. 6). Thus, it seems reasonable to choose a beam thickness of about λ/5 following the compromise: on the one hand, a further decrease in the beam thickness does not significantly improve the situation; on the other hand, this value seems realistic from the point of view of the implementation of the electron-optical system.

6. Preliminary adiabatic estimation of the MIG parameters

First, we consider a gyrotron based on the same magnetic system as in the project of 0.79 THz double-beam gyrotron operating at the second cyclotron harmonic [23]. To ensure high coupling of the two beams with RF field and good enough gyrotron efficiency the following HEBs parameters were chosen: R_{in} = 0.854 mm (0.85 mm), R_{ext} = 1.065 mm (1.07 mm), $g_{in} = g_{ext}$ = 1.3, $\delta v_{\perp in} = \delta v_{\perp ext} \sim 30 - 40\%$, I_{in} , $I_{ext} \geq 0.8$ A. Here the indexes “in” and “ext” correspond to internal and external beams, respectively and the values in brackets correspond to the $TE_{21,4}$ mode. The spreads of the guiding centers ΔR_{in} and ΔR_{ext} should be less than λ/5. Here R_{in}, R_{ext} are partial beams radii, g_{in}, g_{ext} – pitch-factors, I_{in}, I_{ext} – corresponding currents of each beam.

The specified values of the injection radii for both operating modes are very close: the difference in corresponding injection radius is less than λ/50, i.e. 10 times smaller than the admissible value of the guiding centers spread. This allows to design an universal scheme of a double-beam MIG suitable for utilization in the same gyrotron operating at both specified above modes simply by replacing the corresponding cavity inside the tube (to keep the frequency value of about 1.185 THz for the operating mode $TE_{21,4}$ the cavity radius must be equal to 1.492 mm).

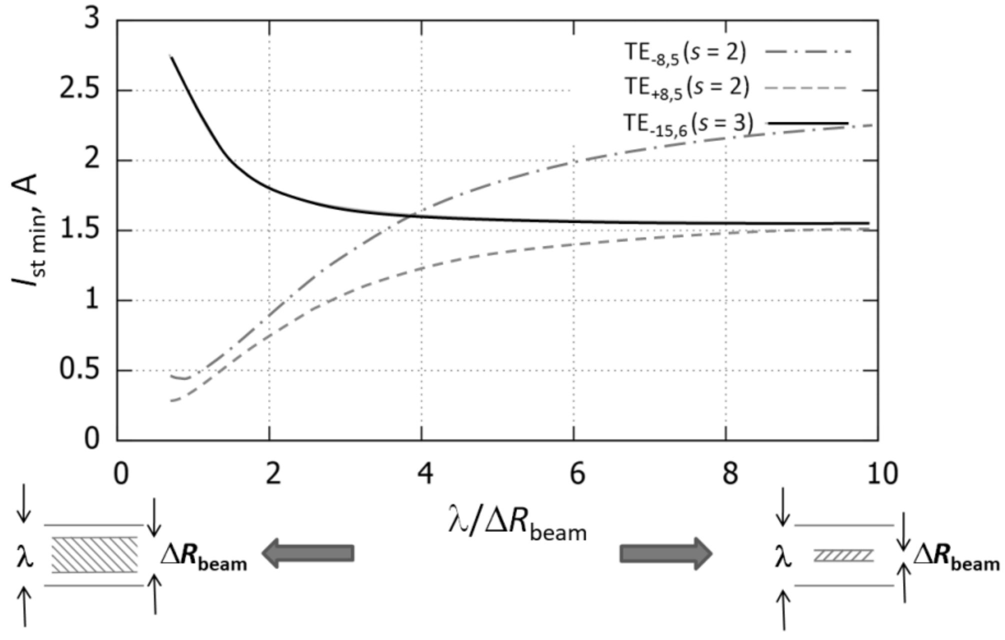

Fig. 6. Minimum value of the starting current $I_{st\ min}$ as a function of the thickness of the electron beam for the operating mode $TE_{-15,6}$ and for the parasitic one $TE_{8,5}$, expressed in wavelengths $\lambda/\Delta R_{beam}$. The same value of $\lambda/\Delta R_{beam}$ corresponds to different values of the magnetic field strength.

Relatively low value of the accelerating (cathode) voltage U_0 should be preferred in order to simplify the gyrotron power supply system [24]. On the other hand, to satisfy the cyclotron resonance condition:

$$\omega \approx 3\omega_c = 3 \cdot \frac{2\pi \cdot 28}{\gamma} \cdot H[\mathrm{T}]$$

for a fixed maximum value of the magnetic field intensity H (which is not higher than 15 T) we need to limit the value of the accelerating potential to approximately 32 kV. Hence, below we consider a version of the beam-shaping system with a total accelerating voltage of 30 kV and a maximum total beam current of 3 A (i.e. in the two HEBs), which are estimated to guarantee an output power of about a hundred watts at least. For a more flexible control of the parameters of the partial HEBs, we consider a triode scheme of the MIG with an anode voltage $U_a \approx 12$ kV.

The preliminary analytical estimation of the operational regime and the MIG dimensions was performed based on the adiabatic theory of HEB formation system [25]. The laminar electron beam was suggested, so the magnetic-field line to the emitter angle φ must be ≥25°. The initial gyrotron parameters, which were further used for analytical estimations, are summarized in Table1, preliminary data of MIG estimations are presented in Table 2.

Table 1.Gyrotron parameters in the interaction space.

Wavelength λ	0.250 mm
Operating magnetic field B_o	14.9 T
Accelerating voltage U_o	30 kV
First-anode potential U_a	12 kV
Beam radii in a cavity R_{ext}(external beam) and R_{in} (internal beam) $TE_{-15,6}$ mode	1.065 mm, 0.854 mm
$TE_{21,4}$ mode	1.070 mm, 0.850 mm
Operating beam currents I_{ext} and I_{in}	1.7 A and 1.3 A
Pitch factors g_1 and g_2	1.3
Magnetic-field line to emitter surface angle φ	≥25°

Table 2.Basic design parameters of the beam shaping system.

Cathode electric field E_c	2.36 kV/mm
Spread of guiding centers in the cavity, ΔR_o(both beams)	$\lambda/5$
Emitter width L (for each beam)	1.0 mm
Current density j_c(for both beams)	3.0 A/cm^2
Ratio $t_j$of thecurrent to the Langmuir current (for both beams)	0.25
Magnetic field compression	
α (external and internal beams)	71.4 and 69.1
Emitter inclination ψ to the axis (external beam)	30°
Cathode radius R_{c2}(external beam)	9.0 mm
Anode radius R_{a2}(external beam)	14.6 mm
Emitter inclination ψ to the axis (internal beam)	25°
Cathode radius R_{c1}(internal beam)	7.1 mm
Anode radius R_{a1}(internal beam)	13.5 mm

It is important to note that the chosen emitter width (1 mm for both beams) satisfies the two formulated above requirements. On the one hand, such width allows to manufacture the emitter ring using the existing technology (manufacturing of smaller ring is a much more complicated task). On the other hand, the restriction imposed by the admissible value of the spread of the guiding centers in the cavity is taken into account as well.

7. Results of the electron trajectory analysis of a double-beam MIG[1]

The second step of the MIG optimization is, as usual, the numerical simulation of the beam properties and optimization of the gun shape.

[1] This section repeats almost *verbatim* the results of the preceding paper in this Newsletter for completeness, consistency and independence of both articles.

In order to simplify the manufacturing of the electron gun and the gyrotron tube itself and to make it cheaper, the distance from the gun to the cavity was kept close to the distance (570 mm) used in the previous version of double-beam gyrotron [23] operating on the second cyclotron harmonic. Besides, the shape of the second anode was preserved the same as well.

The optimization was done using the two-dimensional software EPOS [26]. The final MIG geometry is shown in Fig. 7. The first anode is parallel to the tube axis. The beams parameters calculated according to the model without the initial velocity distribution (such model usually is used during the first step of the optimization) are shown in Table 3. Both beams have very close pitch-factors and smooth dependence of their properties on the operating current.

The calculations show also that the velocity spread $\delta v_{\perp}$ practically does not depend on any kind of the gun geometry deviation caused by a system misalignment or a thermal deformation of the electrodes for both the internal and external electron beams: it varies by no more than on ±(0.3 – 1.0)%. Similarly, the pitch factor varies by no more than ±0.12 when a longitudinal shift of the magnetic system is in the range of ±2 mm. The sensitivity of the pitch-factor to the radial shift of the first anode is significantly higher, especially for the external beam due to the rather small anode-cathode distance and can reach ±0.3. The latter effect, however, can easily be counterbalanced by small variations in the anode potential U_a. Due to the cylindrical form of the first anode the gun is not sensitive to the longitudinal shift of the first anode.

Table 3. Calculated beams parameters in the nominal regime for an anode voltage U_a = 11.73 kV

internal beam				external beam			
jk, A/cm^2	I, A	g	$\delta v_{\perp}$	jk, A/cm^2	I, A	g	$\delta v_{\perp}$
1.0	0.44	1.46	0.03	1.0	0.56	1.44	0.04
1.5	0.65	1.40	0.04	1.5	0.84	1.39	0.05
2.0	0.87	1.34	0.05	2.0	1.12	1.34	0.07
3	1.31	1.24	0.08	3	1.68	1.24	0.10

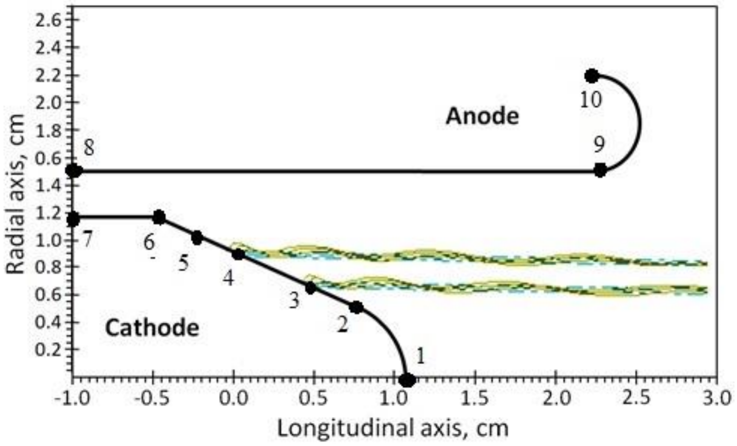

Fig.7. The shape of the electrodes and trajectories of the electrons in the first anode region of double-beam MIG. The anode potential is 11.73 kV.

The key points of the optimized MIG geometry (Fig.7) are given in Table 4, where Z indicate the distance measured from the center of the external emitter, R being the radial position.

Table 4. Position of the key points of the MIG shape

Point number	**1**	**2**	**3**	**4**	**5**
Z, mm	1.066	0.723	0.426	0	-0.31
R, mm	0	0.562	0.689	0.899	0.915
Point number	**6**	**7**	**8**	**9**	**10**
Z, mm	-0.431	-1.0	-1	2.172	2.172
R, mm	1.158	1.17	1.5	1.5	2.3

The final stage of the numerical simulation has been performed using a more sophisticated physical model [25-27] which takes into account such important factors as the thermal velocities of the electrons and the roughness of the emitter surface both leading to a significant increase in the velocity spread [28]. Besides, the specified in Table3 values of the velocity spread are not enough to suppress the excitation of spurious modes at the fundamental cyclotron harmonic [29]. Such suppression is possible only at high enough values of $\delta v_{\perp}$ reaching 30–40%. They can be ensured by the corresponding manufacturing of the emitter with a prescribed (suitable) emitter roughness r_0 (Fig.8). The velocity spread increases with the emitter surface roughness (the corresponding formula is given in [25, 26]) and for the average roughness height $r_0 = 10$ and 20 microns the velocity spread is 27% and 39%, respectively. The specified values of r_0 approximately correspond to the maximum and the minimum admissible values of the velocity spread. Therefore, in the used numerical simulation procedure [26] the width of the initial azimuthal velocity distribution function $f(v_{\theta 0})$ was chosen to provide the specified values of the velocity spread for low currents of the electron beams (I_{in}, $I_{ext} \to 0$).

This procedure [26] allows to find the velocity distribution function in the cavity $F(v_{\perp})=dI/dv_{\perp}$ and thus to calculate the coefficient of reflection K_R from the magnetic mirror for each beam in the operating regime. According to the results of numerical simulation of HEBs with high pitch-factor [30], to avoid the beam instabilities, it is necessary to keep K_R less than 2 – 3%. For an emitter roughness of 20 microns the reflection coefficient is too high (5 – 6%) for any current in both beams. Concurrently, for a roughness of 10 microns in the operating regime with a current density of 3 A/cm^2, the coefficient K_R is small enough (1 – 1.5%) to avoid the beam instability. Thus, one can make the conclusion that the manufacturing technique providing the emitter roughness of 10 microns is quite suitable for meeting the two requirements, namely a rather high pitch-factor and simultaneously a large enough velocity spread and a small reflection coefficient. The value of K_R can be decreased 2 – 3 times by turning to smaller pitch-factors in both beams close to 1.2.

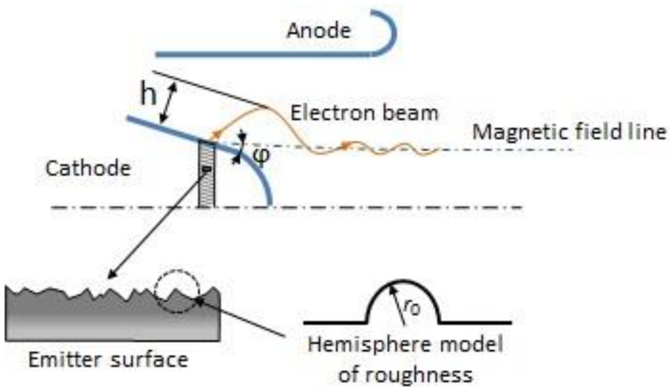

Fig. 8. Electron beam trajectory near the cathode surface and main parameters used for evaluation of the velocity spread caused by the surface roughness

The calculations show that increasing currents in each beam shifts the function $F(v_{\perp})$ simply toward smaller oscillatory velocities, remaining almost Gaussian for both the internal and external beams. This indicates that stable HEBs are formed in the operating regimes of the MIG.

8. Conclusions

Using independent approaches, we have demonstrated the possibility of improvement of the mode selectivity for the case of excitation of a high-order cyclotron harmonic in THz-range gyrotrons by deliberately introducing an appropriate (and large enough) velocity spread in the driving electron beam. Based on these findings, a concept of a novel CW gyrotron capable of operation at the 3rd cyclotron harmonic with the frequency of about 1.2 THz has been proposed. The values of the required velocity spread were determined. The results of numerical simulations show that in order to suppress the spurious modes on the 1st and 2nd cyclotron harmonics, it is necessary to use helical electron beams with velocity spread of about 35-40%. The specified velocity spread can be obtained by using an emitter sponge with a suitable grain size (emitter roughness).

The design of the double-beam electron gun capable of providing the required beams parameters for two operating modes, namely $TE_{-15,6}$ and $TE_{21,4}$ has been proposed. The gun design allows to operate both in single-beam and double-beam versions simply by removing or installing additional emitter on the cathode surface. The roughness of the emitter can be controlled during the manufacturing of the cathode. For LaB_6 cathodes, 30% or 40% velocity spread can be obtained for the grain size of about 10 or 20 micrometer, correspondingly.

It is worth noting that despite the fairly low efficiency, the proposed scheme of high-harmonic THz band generation appears to be very promising and simple in implementation. The output power of the order of several watts significantly exceeds the power provided by the classical electronic devices in this range (for example, BWOs), and is sufficient for many spectroscopic applications, including DNP/NMR spectroscopy.

References

[1] T. Idehara, H. Tsuchiya, O. Watanabe, La Agusu and S. Mitsudo, “The First Experiment of a THz Gyrotron with a Pulse Magnet,” Int. J. Infrared & Millimeter Waves, vol. 27, n. 2 (2006) 319-331. DOI:10.1007/s10762-006-9084-9.

[2] M.Yu. Glyavin, A.G. Luchinin, and G.Yu. Golubiatnikov, “Generation of 1.5-kW, 1-THz Coherent Radiation from a Gyrotron with a Pulsed Magnetic Field,” Phys. Rev. Lett., vol. 100, n. 1 (2008) 015101. DOI:10.1103/PhysRevLett.100.015101

[3] M.Yu. Glyavin, A.G. Luchinin, A.A. Bogdashov, V.N. Manuilov, M.V. Morozkin, Yu. Rodin, G.G. Denisov, D. Kashin, G .Rogers, C.A. Romero-Talamas, R. Pu, A.G. Shkvarunetz, and G.S.Nusinovich "Experimental Study of the Pulsed Terahertz Gyrotron with Record-Breaking Power and Efficiency Parameters," Radiophys. Quantum Electr., vol 56 (2014) 497–507. DOI:10.1007/s11141-014-9454-4.

[4] T. Idehara, M. Glyavin, A. Kuleshov, S. Sabchevski, V. Manuilov, V. Zaslavsly, I. Zotova and A. Sedov, “A Novel THz-Band Double-Beam Gyrotron for High-Field DNP-NMR Spectroscopy,” Rev. Sci. Instr., vol. 88, n. 9 (2017) 094708. DOI:10.1063/1.4997994.

[5] V.L. Bratman, Yu.K. Kalynov, and V.N. Manuilov, “Large-Orbit Gyrotron Operation in the Terahertz Frequency Range,” Phys. Rev. Lett., vol. 102 (2009) 245101. DOI:10.1103/PhysRevLett.102.245101.

[6] Yu.K. Kalynov, V.N. Manuilov, A.Sh. Fiks, and N.A. Zavolskiy “Powerful continuous-wave sub-terahertz electron maser operating at the 3rd cyclotron harmonic,” Appl. Phys. Lett., vol. 114 (2019) 213502. DOI:10.1063/1.5094875.

[7] I. Bandurkin, M. Glyavin, S. Kuzikov, P. Makhalov, I. Osharin, and A. Savilov. “Method of providing the high cyclotron harmonic operation selectivity in a gyrotron with spatially developed operating mode,” IEEE Trans. on Electron Devices, vol. 64, n. 9 (2017) 3893-3897. DOI:10.1109/TED.2017.2731982.

[8] M.M. Melnikova, A.G. Rozhnev, N.M. Ryskin, Y. Tatematsu, M. Fukunari, Y. Yamaguchi, T. Saito “Electromagnetic Modeling of a Complex-Cavity Resonator for the 0.4-THz Second-Harmonic Frequency-Tunable Gyrotron,” IEEE Transactions on Electron Devices, vol. 64, n. 12 (2016) 5141-5146. DOI:10.1109/TED.2017.2764874.

[9] S. Yu, Q. Zhao, T. Zhang, Y. Yang, Y. Zhang, and Z. Wang. “The theoretical investigation and design on 0.42 THz gyrotron with complex cavity,” Terahertz Science and Technology, vol. 9, n. 4 (2016) 149-165. DOI:10.11906/TST.149-165.2016.12.15.

[10] V. I. Shcherbinin, Y. K. Moskvitina, K. A. Avramidis, and J. Jelonnek, “Improved mode selection in coaxial cavities for subterahertz second-harmonic gyrotrons,” IEEE Trans. Electron Devices, vol. 67, n. 7 (2020) 2933-2939. DOI:10.1109/TED.2020.2996179.

[11] V. I. Shcherbinin, V. I. Tkachenko, K. A. Avramidis, and J. Jelonnek, “Coaxial cavity with stepped inner conductor for a sub-terahertz second-harmonic gyrotron with broadband continuous frequency tuning,” IEEE Trans. Electron Devices, vol. 66, n. 12 (2019) 5313-5320. DOI:10.1109/TED.2019.2944647.

[12] I.I. Antakov, V.S. Ergakov, E.V. Zasypkin, and E.V. Sokolov, “Starting conditions of a CRM monotron in the presence of scatter of the velocities of the electrons,” Radioph.&Quant. Electr., vol. 20, n. 4 (1977) 413-418. DOI:10.1007/BF01033931.

[13] M. Yeddulla, G.S. Nusinovich, and T.M. Antonsen, "Start Currents in an Overmoded Gyrotron”, Phys. Plasmas 10, 4513-4520 (2003); DOI:10.1063/1.1618777.

[14] G.F. Brand, P.W. Fekete, K. Hong, K.J. Moore, and T. Idehara, “Operation of a tunable gyrotron at the second harmonic of the electron cyclotron frequency,” Int. J. Electronics, vol. 68, n. 6 (1990) 1099-1111.

[15] https://www.3ds.com/products-services/simulia/products/cst-studio-suite/

[16] N.A. Zavolsky, V.E. Zapevalov, and M.A. Moiseev, “Efficiency enchamcement of the relativistic gyrotron,” Radiophys.and Quant. Electr., vol. 44, n. 4 (2001) 318.

[17] G.S.Nusinovich, “Introduction to Physics of Gyrotons”, J. Hopkins Univ. Press, Baltimore-London, 2004.

[18] O. Dumbrajs , T. Saito , Y. Tatematsu , and Y. Yamaguchi, “Influence of the Electron Velocity Spread and the Beam Width on the Efficiency and Mode Competition in the High-Power Pulsed Gyrotron for 300 GHz Band Collective Thomson Scattering Diagnostics in the Large Helical Device,” Phys. Plasmas vol. 23 (2016) 093109. DOI:10.1063/1.4962575.
[19] N. S. Ginzburg, A. S. Sergeev, and I. V. Zotova, “Time-domain self-consistent theory of frequency-locking regimes in gyrotrons with low-Q resonators,” Phys. Plasmas, vol. 22 (2015) 033101. DOI:10.1063/1.4913672.
[20] N.S. Ginzburg, G.S. Nusinovich, N.A. Zavolsky, “Theory of non-stationary processes in gyrotrons with low Q resonators,” Int. J. of Electronics, vol. 61 (1986) 881.
[21] V.Zaslavsky, N.Ginzburg, M.Glyavin, I.Zheleznov, I.Zotova, "Three-dimensional particle-in-cell modeling of terahertz gyrotrons with cylindrical and planar configurations of the interaction space," Phys. Plasmas, vol. 20 (2013) 043103.
[22] O. Dumbrajs, T. Idehara, T. Saito, and Y. Tatematsu, “Calculations of Starting Currents and Frequencies in Frequency-Tunable Gyrotrons,” Jpn. J. Appl. Phys., vol. 51 (2012) 126601.
[23] V.N. Manuilov, M.Yu. Glyavin, A.S. Sedov, V.Yu. Zaslavsky, T. Idehara, “Design of a Second Harmonic Double-Beam Continuous Wave Gyrotron with Operating Frequency of 0.79 THz,” J. Infrared Millim. Terahertz Waves, vol. 36, n. 12 (2015) 1164-1175.
[24] M.Glyavin, N.Zavolsky, A.Sedov, G.Nusinovich, “Low voltage gyrotrons,” Physics of plasmas, vol. 20, n. 3 (2013) 033103.
[25] Sh.E. Tsimring, Electron Beams and Microwave Vacuum Electronics. Hoboken, NJ: John Wiley & Sons. Inc. (2007)
[26] P.V. Krivosheev, V.K. Lygin,V.N. Manuilov, Sh.E. Tsimring, “Numerical Simulation Models of Forming Systems of Intense Gyrotron Helical Electron Beams,” Int. J. Infrared Milli. Waves, vol. 22 (2001) 1119-1145.
[27] V.K. Lygin, “Numerical simulation of intense helical electron beams with the calculation of the velocity distribution functions,” Int. J. Infrared Milli. Waves, vol. 16 (1995) 363-376.
[28] Sh.E. Tsimring, “On the spread of velocities in helical electron beams,” Radiophys. Quantum Electron, vol. 15 (1972) 952-961.
[29] M. Yeddulla, G.S. Nusinovich, T.M. Antonsen, “Start currents in an overmoded gyrotron,” Phys. Plasmas, vol. 10 (2003) 4513.
[30] V.N. Manuilov, “Numerical simulation of low-frequency oscillations of the space charge and potential in the electron-optical system of a gyrotron,” Radiophys. Quantum Electron., vol. 49 (2006) 786-792. DOI:10.1007/s11141-006-0113-2.

More detail on the project:

1. V.N. Manuilov, A.I. Tsvetkov, M.Yu. Glyavin, S. Mitsudo, T. Idehara, I.V. Zotova, “Universal Electron Gun Design for a CW Third Harmonic Gyrotron with an Operating Frequency over 1 THz,” Journal of Infrared, Millimeter, and Terahertz Waves, vol. 41 (2020) 1121–1130. DOI: 10.1007/s10762-020-00702-5.
2. I. Bandurkin, M. Glyavin, T. Idehara, A. Malkin, V. Manuilov, A. Sergeev, A. Tsvetkov, V. Zaslavsky, I. Zotova, “Development of Third-Harmonic 1.2-THz Gyrotron With Intentionally Increased Velocity Spread of Electrons,” IEEE Trans Electronic Devices, vol. 67, n. 10 (2020) 1557-9646. DOI:10.1109/TED.2020.3012524.

FORTHCOMING EVENTS (UPDATED ANNOUNCEMENTS)

11th International Workshop

MMW 2020

Strong Microwaves and Terahertz Waves: Sources and Applications

July 5–10, 2020

Nizhny Novgorod, Russia

Announcement by the organizers: “We regret to inform you that because of the significant health risks and transportation disruptions associated with the COVID-19 pandemic we are forced to **postpone the 11th International Workshop “Strong Microwaves and Terahertz Waves: Sources and Applications” until summer 2021**.

We will inform you about the planned dates for the Workshop as soon as they are available. Please visit the website of the Workshop.

Thank you for your interest in our Workshop and hope to see all of you in Nizhny Novgorod next summer.”

IW-FIRT2021

The 8th International Workshop on Far-Infrared Technologies (IW-FIRT 2021) (March 8-9, 2021, University of Fukui, Fukui, Japan)

The first International Workshop on Far-Infrared Technologies (IW-FIRT) was held in 1999 as a celebration event for establishing FIR FU, and the second IW-FIRT was held in 2002 as a part of the Fukui University International Congress to celebrate the 50th anniversary of our university. The third IW-FIRT was held in 2010, eight years after the second IW-FIRT, to commemorate the 10th anniversary of the foundation of FIR UF. The fourth, fifth, and sixth IW-FIRT were held in 2012, 2014, 2017, and 2019, successively, every few years. In these workshops it was aimed to discuss the recent developments and future directions of far-infrared and terahertz science and technologies with a special emphasis on high power radiation sources in this frequency region and their applications. We feel that it is the time to organize the next IW-FIRT to update our knowledge and understanding in this rapidly developing field. Therefore, we organize the 8th International Workshop on Far-Infrared Technologies (IW-FIRT 2021). **In view of the pandemic of COVID-19 the Workshop will be held on 8 and 9 March 2021 online via Zoom. For more detail please visit the website of the Workshop.**

SPECIAL JOURNAL ISSUES IN THE FIELD OF THZ SCIENCE

Special Issue "Design, Technologies and Applications of High Power Vacuum Electronic Devices from Microwave to THz Band". For more detail, please follow the link.

electronics

an Open Access Journal by MDPI

IMPACT FACTOR 2.412

Design, Technologies and Applications of High Power Vacuum Electronic Devices from Microwave to THz Band

Guest Editor:

Prof. Dr. Mikhail Glyavin
Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russia

glyavin@appl.sci-nnov.ru

Deadline for manuscript submissions:
31 January 2021

Message from the Guest Editor

The last decade has contributed to the rapid progress in the development of high-power microwave sources, in particular of gyrotrons. This Special Issue aims to bring together information about the most striking theoretical and experimental results, new trends in development, modern remarkable applications, new demands in parameter enhancement, and future goals. Therefore, researchers are invited to submit their manuscripts to this Special Issue and contribute their models, proposals, reviews, and studies.

Special Issue "Terahertz Optical Elements: Science and Technology". For more detail, please follow the link.

applied sciences

an Open Access Journal by MDPI

IMPACT FACTOR 2.474

Terahertz Optical Elements: Science and Technology

Guest Editor:

Prof. Svilen Petrov Sabchevski
Laboratory "Plasma Physics and Engineering", Institute of Electronics, Bulgarian Academy of Sciences, 1784-Sofia, Bulgaria

sabch@ie.bas.bg

Deadline for manuscript submissions:
28 February 2021

Message from the Guest Editor

In any system utilizing THz waves, the optical elements for shaping and manipulating the THz wave beam are indispensable components. This Special Issue is devoted to their fundamental principles and the current state-of-the-art in their development, investigation, manufacturing, and usage.

Areas of interest include (but are not limited to) the following main topics:

- Fundamentals and physical principles of the THz optics
- Terahertz sources and detectors
- Focusing lenses for THz waves
- Diffractive THz optical elements (e.g., beam homogenizers), collimators, beam splitters, reflectors, polarizers, attenuators, filters
- Computational design of THz optical and quasi-optical elements
- Materials (including metamaterials) and advanced technologies (e.g. 3D-printing technology, laser treatment, etc.) for precise fabrication of THz optical components
- Production of optical elements for THz systems (scanners, cameras, imaging, and inspection devices)

Academician Professor Alexander Litvak at 80

On November 17, 2020, Alexander Grigorievich Litvak turns 80 - an outstanding physicist, academician of the Russian Academy of Sciences, member of the Presidium of the Russian Academy of Sciences (RAS), member of the Bureau of the Physical Sciences Division of the Russian Academy of Sciences, scientific director of the Federal Research Center of the Institute of Applied Physics of the Russian Academy of Sciences (IAP RAS), Doctor of Phys.-Math. Sciences, Professor.

In 1962, A.G. Litvak graduated from the radiophysical faculty of the Gorky State University named after N.I. Lobachevsky and entered graduate school under the guidance of Professor M.A. Miller. In 1967, A. Litvak defended his Ph.D. thesis "Some questions of the theory of nonlinear electromagnetic phenomena in plasma", and in 1977 - the thesis "Self-action and interaction of electromagnetic waves in plasma" for the degree of Doctor of Phys.-Math. Sciences. Since 1977, in the newly organized Institute of Applied Physics of the Academy of Sciences of the USSR, A.G. Litvak has consistently headed the sector, laboratory, and plasma physics department. In 1988, A.G. Litvak became the head of the Department of Plasma Physics and High Power Electronics, and since 2003, for 12 years, he was Director of the Institute of Applied Physics of the Russian Academy of Sciences, and since May 2015 a Scientific Director of the Institute. In 2016, Academician Alexander Litvak was awarded the title "Honorary Professor of the Lobachevsky State University of N. Novgorod.

A. G. Litvak is a prominent, widely recognized specialist in the field of plasma physics, physical electronics and radiophysics. The scientific activity of A.G. Litvak covers a wide range of problems, such as the interaction of powerful electromagnetic radiation with matter, the development and creation of dense plasma sources, the development of microwave methods for heating of plasma in controlled thermonuclear fusion installations, the development of powerful microwave radiation sources and their use for creating new technologies.

Already at the first stage of his scientific activity, A.G. Litvak carried out fundamental work on nonlinear electrodynamics of plasma and condensed matter. He formulated averaged dynamic equations for plasma and field, which made it possible to study from a unified standpoint the processes of self-focusing and stimulated scattering of electromagnetic waves in isotropic and magnetoactive plasmas, developed a theory of self-channeling of intense electromagnetic waves in opaque supercritical plasma, and for the first time studied the effects of self-action of relativistically strong waves associated with the dependence of the mass of an electron on the energy of vibrations in the wave field. These effects determine the nature of the interaction of ultra-high-power laser pulses with plasma in modern experiments aimed at developing new methods for accelerating particles and studying extreme states of matter.

In the same years, A.G. Litvak investigated a number of important effects in the field of nonlinear optics. He predicted the effect of thermal self-focusing and constructed its theory, formulated (together with V.I. Talanov) an equation of the type of a nonlinear Schrödinger equation to describe the self-action of three-dimensional wave packets in nonlinear media, and on its basis developed the theory of modulation instability of non-dimensional wave packets, showed the existence of nonlinear surface polaritons - electromagnetic surface waves that have no linear analogue.

A. G. Litvak has the priority of setting up complex experimental studies of the interaction of high-power microwave radiation with plasma. He and his colleagues were the first to experimentally discover and study the effects of self-focusing of waves in a plasma and nonlinear transparency of dense "supercritical" plasma, modulation instability of Langmuir oscillations, and dynamics of a Langmuir caviton. Their investigations of the nonlinear dynamics of a freely localized gas discharge in beams of electromagnetic waves laid the foundations for a new field of low-temperature plasma physics, extremely rich in various applications: from the production of beams of multiply charged ions for high-energy accelerators to the purification of the upper atmosphere from environmentally harmful impurities and ozone regeneration.

In the field of controlled thermonuclear fusion, A.G. Litvak and co-authors developed the foundations of the theory of electron-cyclotron (EC) heating of plasma by quasi-optical beams of electromagnetic waves and demonstrated the possibility of plasma heating in toroidal installations when radiation is input from a weak magnetic field. These proposals, confirmed by experiments on the T-10 tokamak at the Kurchatov National Research Center, served as the basis for the widespread use of EC heating and non-induction current generation in modern toroidal CTS installations.

A team of highly qualified theorists and experimenters was formed under the leadership of A.G. Litvak, who achieved noticeable success in the creation of powerful sources of microwave radiation and the development of their applications in radar, plasma physics and nuclear physics, in technologies for obtaining new materials. Among the most important results in this area should be noted the development and introduction into production of quasi-cw gyrotrons of megawatt power level. On the initiative of A.G. Litvak, the the Closed Joint-Stock Company "Scientific Production Enterprise 'GYCOM' (Gyrotron Complexes)" (GYCOM Ltd.) was established. Its high-tech production made it possible to equip about fifteen domestic and foreign tokamaks and stellarators with efficient EC systems based on powerful gyrotrons. At present, A.G. Litvak and his colleagues are completing the creation of a continuous megawatt gyrotron at a frequency of 170 GHz for the international ITER project and a megawatt gyrotron with a stepwise tuning of the radiation frequency in the range from 105 to 150 GHz. Remarkable progress has been achieved in the development of sources of dense nonequilibrium plasma based on gyrotrons of a new generation, technologies for sintering of nanoceramic materials and high-speed growth of polycrystalline diamond films and plates, and diamond single crystals.

In recent years, A.G. Litvak and his co-workers have launched research on the creation and application of terahertz radiation sources associated both with the advancement of traditional methods of high-power vacuum electronics to the region of higher frequencies and with the use of detection of femtosecond laser pulses in nonlinear media. The possibilities of realizing the basic elements of quantum communications and computations based on impurity centers in solids (inorganic crystals activated by rare-earth metals, vacancy centers in diamond) are investigated. Qubits, quantum memory on the spectral lattice of rare-earth metal ions embedded in an inorganic crystal have been implemented, a new tomography method for an optically controlled qubit has been proposed, and the possibility of implementing three-qubit operations has been experimentally demonstrated. A laboratory model of an atomic clock based on coherent population trapping on rubidium vapor has been developed, demonstrating a stability at the level of 3×10^{-11} per 1000 sec.

The results of A.G. Litvak's research have been published in more than 300 scientific papers, implemented in numerous unique instrumental and hardware complexes. His scientific achievements were noted in the team of authors by the USSR State Prize in Science and Technology for the cycle of works "Fundamentals of nonlinear dynamics of high-frequency wave processes in fully ionized plasma" (1987), the Russian Federation Government prize in the field of science and technology "For the development and development of industrial production megawatt gyrotrons for electron-cyclotron plasma heating in large-scale controlled thermonuclear fusion installations "(2012), a prestigious international prize named after Kenneth Button, Outstanding Contribution to the Science of Electromagnetic Waves (2008).

A.G. Litvak pays much attention to the education and training of young scientific personnel. Among his students there is a corresponding member of the Russian Academy of Sciences, more than 20 doctors (DSc and PhD). He is the founder and head of the well-known and one of the largest in Russia scientific school in the field of plasma physics, which includes about 30 actively working researchers many of which young scientists. A.G. Litvak is the organizer and the first dean of the basic faculty of the IAP RAS "Higher School of General and Applied Physics" at Nizhny Novgorod State University. He created the IAP RAS Scientific and Educational Complex, which implements an effective continuous system of training for scientific personnel for work in the field of physics. The complex includes specialized senior classes of physical and mathematical sciences

A.G. Litvak is doing a lot of scientific and organizational work. He played a decisive role in the formation of the largest Branch of the IAP RAS - the Branch of Plasma Physics and High Power Electronics. As director of the IAP, A.G. Litvak successfully solved the problems of economic, personnel and scientific support and development of the institute, which, despite the difficulties of recent years, has retained its leading positions in world science in the field of physics of oscillatory and wave processes. He is doing a lot of work on the coordination of research and the establishment of effective scientific and industrial relations of the Institute with leading research centers and industrial enterprises of Russia.

AG Litvak is the initiator of the organization in 2008 of the Nizhny Novgorod Scientific Center of the Russian Academy of Sciences, which consolidated the intellectual and technological potential of the academic institutions of Nizhny Novgorod. On his initiative, under the auspices of the NSC RAS in the Nizhny Novgorod region, activities in the field of popularizing scientific knowledge were actually revived and the Scientific and Educational Center "Knowledge - NN" was created.

A.G. Litvak is a world-renowned scientist. He is the chairman and member of the program committees of a number of international scientific conferences and meetings, including the traditionally held IAP RAS conferences "Frontiers of Nonlinear Physics" and "Intense Microwave Radiation: Sources and Applications", which have a high international rating, a member of the editorial boards of a number of international and domestic scientific journals, a member of the Council of the Russian Foundation for Basic Research. In recognition of the merits of A.G. Litvak, he was awarded the Medal of Friendship in 2004, the Medal of Merit for the Fatherland, IV degree in 2010, and in 2006 he was awarded the title of Honorary Citizen of the Nizhny Novgorod Region.

In 2005, Professor Litvak was a member of the International Check and Review Committee, which evaluated positively the research carried out at FIR UF Center during the first five years since its establishment.

As a Director of IAP-RAS, Professor Litvak has always been an active supporter of the international collaboration between scientists from IAP and FIR UF Research Center.

The friends and colleagues of A.G. Litvak, his numerous students and followers congratulate him on his 80th birthday and wish him good health and long life, as well as new remarkable achievements!

LIST OF SELECTED RECENT PUBLICATIONS

Bibliography and links to selected recent publications on topics related to the research field of the International Consortium and published after June 2020, i.e. after issuing the previous Newsletter #15. This cumulative list is in chronological order as collected from various bibliographical and alert services

A. Publications by authors from the institutions participating in the International Consortium

Y. Yamaguchi, T. Ogura, T. Ueyama, Y. Maeda, K. Takayama, J. Sasano, M. Fukunari, Y. Tatematsu, T. Saito, "Super Multi-Frequency Oscillations at Fundamental Harmonics with a Complex Cavity Gyrotron," IEEE Electron Device Letters, (2020). DOI:10.1109/LED.2020.3000640.
https://ieeexplore.ieee.org/document/9110568

Kojima, M., Suzuki, Y., Tasaki, T. et al., “Clinical Course of High-Frequency Millimeter-Wave (162 GHz) Induced Ocular Injuries and Investigation of Damage Thresholds,” J Infrared, Millimeter, and Terahertz Waves (2020). DOI:10.1007/s10762-020-00714-1.
https://link.springer.com/article/10.1007/s10762-020-00714-1

G. Aiello, S. Schreck, K.A. Avramidis, T. Franke, G. Gantenbein, J. Jelonnek, A. Meier, T. Scherer, D. Strauss, M. Thumm, M.Q. Tran, C. Wild, E. Woerner, “Towards large area CVD diamond disks for Brewster-angle windows,” Fusion Engineering and Design, vol. 157 (2020) 111818. DOI:10.1016/j.fusengdes.2020.111818.
http://www.sciencedirect.com/science/article/pii/S0920379620303665

Girka I.O., Girka O.I., Thumm M., “Azimuthal surface waves in cylindrical metal waveguides partially filled by magnetoactive plasma: Analysis of energy transfer,” Physics of Plasmas, vol. 27, n. 6 (2020) 062108. DOI: 10.1063/5.0009220.
https://aip.scitation.org/doi/10.1063/5.0009220

S.V. Samsonov, K.A. Leshcheva, V.N. Manuilov, "Multitube Helical-Waveguide Gyrotron Traveling-Wave Amplifier: Device Concept and Electron-Optical System Modeling," in IEEE Transactions on Electron Devices, (2020). DOI:10.1109/TED.2020.3001491.
https://ieeexplore.ieee.org/document/9125999

Gashturi A.P., Nusinovich G.S., Zotova I.V., Semenov E.S., Sabchevski S.P., Glyavin M.Yu., “Nonlinear excitation of parasitic modes in harmonic gyrotrons,” Physics of Plasmas, vol. 27, n. 6 (2020) 063304. DOI: 10.1063/5.0010593
https://aip.scitation.org/doi/abs/10.1063/5.0010593

S.V. Samsonov, G.G. Denisov, I.G. Gachev, A.A. Bogdashov, "CW Operation of a W-Band High-Gain Helical-Waveguide Gyrotron Traveling-Wave Tube," in IEEE Electron Device Letters, vol. 41, n. 5 (2020) 773-776. DOI:10.1109/LED.2020.2980572.
https://ieeexplore.ieee.org/document/9035466

Glyavin M., Sabchevski S., Idehara T., Mitsudo S., “Gyrotron-Based Technological Systems for Material Processing—Current Status and Prospects,” J Infrared, Millimeter, and Terahertz Waves, (2020). DOI:10.1007/s10762-020-00727-w.
https://link.springer.com/article/10.1007/s10762-020-00727-w

Fokin A.P., Glyavin M.Yu., Manuilov V.N., Osharin I.V., Savilov A.V., "On applicability of absorbing rectilinear electron beams in high-frequency gyrotrons operating at cyclotron harmonics," Physics of Plasmas, vol. 27, n. 6 (2020) 064501. DOI: 10.1063/5.0006108.
https://aip.scitation.org/doi/10.1063/5.0006108

Glyavin, M., Zotova, I., Rozental, R., Malkin A., Sergeev A., Fokin A., Rumyantsev V., Morozov S., “Investigation of the Frequency Double-Multiplication Effect in a Sub-THz Gyrotron,” J Infrared, Millimeter, and Terahertz Waves (2020). DOI:10.1007/s10762-020-00726-x.
https://link.springer.com/article/10.1007/s10762-020-00726-x

Nusinovich G.S., Chen X., Dumbrajs O., Xiao H., “Zones of soft and hard self-excitation in gyrotrons: Generalized approach,” Physics of Plasma, vol. 27, n. 7 (2020) 073103. DOI:10.1063/5.0010377.
https://aip.scitation.org/doi/full/10.1063/5.0010377

Girka I.O., Girka O.I., Thumm, M., “Azimuthal surface waves in cylindrical metal waveguides partially filled by magnetoactive plasma: Analysis of energy transfer,” Physics of Plasmas, vol. 27, n. 6 (2020), 062108. DOI: 10.1063/5.0009220.
https://aip.scitation.org/doi/10.1063/5.0009220

I.V. Bandurkin, A.P. Fokin, M.Yu. Glyavin, A.G. Luchinin, I.V. Osharin, A.V. Savilov, “Demonstration of a Selective Oversized Cavity in a Terahertz Second-Harmonic Gyrotron,” IEEE Electron Device Letters, (2020). DOI: 10.1109/LED.2020.3010445.
https://ieeexplore.ieee.org/document/9144296

Y K. Kalynov, I.V. Osharin, A.V. Savilov, "Competition of Oscillations at Different Cyclotron Harmonics in the Subterahertz Large-Orbit Gyrotron," IEEE Transactions on Electron Devices, (2020). DOI:10.1109/TED.2020.3009617.
https://ieeexplore.ieee.org/document/9153149

I. Bandurkin, A. Fedotov, M. Glyavin, T. Idehara, A. Malkin, V. Manuilov, A. Sergeev, A. Tsvetkov, V. Zaslavsky, Zotova, "Development of Third-Harmonic 1.2-THz Gyrotron With Intentionally Increased Velocity Spread of Electrons," in IEEE Transactions on Electron Devices, (2020). DOI:10.1109/TED.2020.3012524.
https://ieeexplore.ieee.org/document/9160870

A.V. Palitsin, Y.V. Rodin, A.G. Luchinin, A.N. Panin, V.L. Bakunin, Y.V. Novozhilova, A.V. Gromov, M.B. Goykhman, A.S. Zuev, M.Yu. Glyavin, "Experimental study of multi-mode dynamics of THz-band pulsed magnetic field gyrotron," in IEEE Electron Device Letters, vol. 41, n. 10 (2020) 1576-1579. DOI:10.1109/LED.2020.3018551.
https://ieeexplore.ieee.org/document/9173707

Vodopyanov A. V., Mansfeld D. A., Tsvetkov A. I., “Peculiarities of Pulsed Heating by the Radiation of a Subterathertz Gyrotron in the Production of Metal Oxide Nanopowders,” Technical Physics Letters, vol. 46, n. 8 (2020) 760-763. DOI:10.1134/S1063785020080155. (Russian Text published in Pis’ma v Zhurnal Tekhnicheskoi Fiziki, 2020, Vol. 46, No. 15, pp. 33–35).
http://tiny.cc/3a7rsz

T. Kawasaki, Y. Yamaguchi, T. Ueda, Y. Ishikawa, T. Yaji, T. Ohta, K. Tsukiyama, T. Idehara, M. Saiki, M. Tani, “Irradiation effect of a submillimeter wave from420 GHz gyrotron on amyloid peptides in vitro,” Biomedical Optics Express, vol. 11, n. 9 (2020) 5341. DOI: 10.1364/BOE.395218.
https://www.osapublishing.org/boe/abstract.cfm?uri=boe-11-9-5341

Sidorov A., Razin S., Veselov A., Viktorov M., Vodopyanov A., Luchinin A., Glyavin M., "Dynamics of the gas discharge in noble gases sustained by the powerful radiation of 0.67 THz gyrotron," Physics of Plasmas, vol. 27, n. 9 (2020) 093509. DOI:10.1063/5.0012583.
https://aip.scitation.org/doi/10.1063/5.0012583

M. Glyavin, V. Manuilov, E. Taradaev, G. Sominskii, A. Fokin, A. Sedov, “Design of a pulsed 0.5 THz gyrotron and preliminary test of its electron gun with field emitter,” Infrared Physics & Technology, (2020) 103480. DOI:10.1016/j.infrared.2020.103480.
http://www.sciencedirect.com/science/article/pii/S1350449520305284

Maremyanin K.V., Parshin V.V., Serov E.A. et al., “Investigation into Microwave Absorption in Semiconductors for Frequency-Multiplication Devices and Radiation-Output Control of Continuous and Pulsed Gyrotrons,” Semiconductors, vol. 54 (2020) 1069–1074. DOI:10.1134/S1063782620090195.
https://link.springer.com/article/10.1134/S1063782620090195

Manuilov V.N., Tsvetkov A.I., Glyavin M.Y. et al., “Universal Electron Gun Design for a CW Third Harmonic Gyrotron with an Operating Frequency over 1 THz,” Journal of Infrared, Millimeter, and Terahertz Waves, vol. 41 (2020) 1121–1130. DOI:10.1007/s10762-020-00702-5.
https://link.springer.com/article/10.1007/s10762-020-00702-5?utm_source=toc

Denisov G.G., Glyavin M.Y., Fedotov A.E. et al.,”Theoretical and Experimental Investigations of Terahertz-Range Gyrotrons with Frequency and Spectrum Control,” Journal of Infrared, Millimeter, and Terahertz Waves, vol. 41 (2020) 1131–1143. DOI:10.1007/s10762-020-00672-8.
https://link.springer.com/article/10.1007/s10762-020-00672-8?utm_source=toc&utm_medium=email&utm_campaign=toc_10762_41_9&utm_content=etoc_springer_20200916

I.V. Osharin, A.V. Savilov, “Frequency tuning in short-wave gyrotrons,” Radiophysics and Quantum Electronics, vol. 62, n. 11 (2020). DOI: 10.1007/s11141-020-10020-4.
https://link.springer.com/article/10.1007%2Fs11141-020-10020-4

Zavol’sky N.A., Zapevalov V.E., Kuftin A.N., Postnikova A.S., “Numerical Simulation and Experimental Study of High-Power Gyrotrons with Energy Recovery,” Radiophysics and Quantum Electronics, vol. (2020). DOI:10.1007/s11141-020-10021-3.
https://link.springer.com/article/10.1007%2Fs11141-020-10021-3

Gavrilenko V., Glyavin M., Shkurinov A., “Editorial Introduction to the Special Issue: THz Summer 2019 in Russia,” Journal of Infrared, Millimeter, and Terahertz Waves, vol. 41, (2020) 1039–1040. DOI:10.1007/s10762-020-00741-y.
https://link.springer.com/article/10.1007/s10762-020-00741-y

Serov E.A., Parshin V.V., Vlasova K.V. et al., “Modern Dielectric Materials for Output Windows of High-Power Microwave and Terahertz Sources,” Journal of Infrared, Millimeter, and Terahertz Waves, vol. 41, (2020). DOI:10.1007/s10762-020-00745-8.
https://link.springer.com/article/10.1007/s10762-020-00745-8

Bakunin V.L., Glyavin M.Yu., Denisov G.G., Novozhilova Y.V., "Investigation of mode interaction for a gyrotron with dense mode spectrum," Journal of Electromagnetic Waves and Applications, (2020). DOI: 10.1080/09205071.2020.1821790.
https://www.tandfonline.com/doi/full/10.1080/09205071.2020.1821790

Manuilov V.N., Fedotov A.E., Zotova I.V., Rozental R.M., Idehara T., Mitsudo S., Glyavin M.Yu., “Magnetron-Injection Gun with Increased Current for Frequency Tunable Medium Power Sub-THz Gyrotron,” Journal of Infrared, Millimeter, and Terahertz Waves, (2020). DOI:10.1007/s10762-020-00746-7.
https://link.springer.com/article/10.1007/s10762-020-00746-7

Kulygin M.L., Litovsky I.A., “Sub-Terahertz Complex Permittivity Measurement Method Using Cavity Switches,” J Infrared Milli Terahz Waves (2020). DOI:10.1007/s10762-020-00742-x.
https://link.springer.com/article/10.1007%2Fs10762-020-00742-x

A.S. Zuev, A.S. Sedov, E.S. Semenov, A.P. Fokin, M.Y. Glyavin, "Analysis of the Possibilities to Control Diffraction Quality Factors of the Cavities of Subterahertz Gyrotrons," in IEEE Transactions on Plasma Science, (2020). DOI: 10.1109/TPS.2020.3025689.
https://ieeexplore.ieee.org/abstract/document/9210040

S.V. Egorov, A.G. Eremeev, V.V. Kholoptsev, I.V. Plotnikov, K.I. Rybakov, A.A. Sorokin, S.S. Balabanov, E.Ye. Rostokina, Yu.V. Bykov, “Rapid microwave sintering of alumina ceramics with an addition of carbon nanotubes,” Ceramics International, (2020). DOI:10.1016/j.ceramint.2020.10.027.
http://www.sciencedirect.com/science/article/pii/S0272884220330674

B. Publications by other authors worldwide

S. Ullah, C. Ruan, M.S. Sadiq, T.U. Haq, W. “Microstrip system on-chip circular polarized (CP) slotted antenna for THz communication application,” Journal of Electromagnetic Waves and Applications, (2020) DOI: 10.1080/09205071.2020.1770130.
https://www.tandfonline.com/doi/abs/10.1080/09205071.2020.1770130?journalCode=tewa20

X. Liao, Z. Wu, M. Wang, Y. Pu, W. Jiang and Y. Luo, "Synthesis of Broadband Oversized Smooth-Walled Horn for High-Power Millimeter Wave," in IEEE Transactions on Microwave Theory and Techniques, (2020). DOI:10.1109/TMTT.2020.2995720.
https://ieeexplore.ieee.org/abstract/document/9106768

Y. Oda, M. Takahashi, N. Ohnishi, K. Komurasaki, K. Sakamoto, T. Imai, "A study on the macroscopic self-organized structure of high-power millimeter-wave breakdown plasma," Plasma Sources Science and Technology (2020). DOI: 10.1088/1361-6595/ab9d67.
https://iopscience.iop.org/article/10.1088/1361-6595/ab9d67

Y. Annaka, et al., "Design and Fabrication of 200-GHz Oversized Surface-Wave Oscillator," in IEEE Transactions on Plasma Science, (2020). DOI:10.1109/TPS.2020.2998119.
https://ieeexplore.ieee.org/abstract/document/9109707

H. V. Dhuda, P. N. Patel and H. B. Pandya, "Modified Corrugation-Based W-Band Waveguide With Selective Notched Operation for Fusion Plasma Diagnostics," in IEEE Transactions on Plasma Science, (2020). DOI:10.1109/TPS.2020.2998288.
https://ieeexplore.ieee.org/abstract/document/9109686

Akash and M. Thottappan, "Design and Efficiency Enhancement Studies of Periodically Dielectric Loaded W-Band Gyro-TWT Amplifier," in IEEE Transactions on Electron Devices, vol. 67, n. 7 (2020) 2925-2932. DOI: 10.1109/TED.2020.2996191.
https://ieeexplore.ieee.org/abstract/document/9107343

V.I. Shcherbinin, Y.K. Moskvitina, K.A. Avramidis, J. Jelonnek, "Improved Mode Selection in Coaxial Cavities for Subterahertz Second-Harmonic Gyrotrons," in IEEE Transactions on Electron Devices, vol. 67, n. 7 (2020) 2933-2939. DOI:10.1109/TED.2020.2996179.
https://ieeexplore.ieee.org/abstract/document/9108542

G. Zhao, H. Yang, Q. Xue , L. Chen, "Study on Beam-shaping Mirrors for Gaussian Beams at Frequency of 170GHz," 2020 IEEE 3rd International Conference on Electronics Technology (ICET), Chengdu, China (2020) 190-193,DOI:10.1109/ICET49382.2020.9119639.
https://ieeexplore.ieee.org/abstract/document/9119639

Dhuda H.V., Patel, P.N., Pandya H.B., "A Constant Corrugation Circular Waveguide for High-Pass Signal Diagnostics in ECEI System at 75–110 GHz,"J Infrared, Millimeter, and Terahertz Waves (2020). DOI:0.1007/s10762-020-00720-3.
https://link.springer.com/article/10.1007/s10762-020-00720-3

J. Yan et al., "A Method for Accurately Characterizing Single Overmoded Circular TM01-TE11 Mode Converter," in IEEE Access, vol. 8 (2020) 113383-113391. DOI:10.1109/ACCESS.2020.3002501.
https://ieeexplore.ieee.org/document/9123399

M. Zarghani, S. Mohsenzade and S. Kaboli, "A High Voltage Pulsed Power Supply with Online Rise Time Adjusting Capability for Vacuum Tubes," in IEEE Journal of Emerging and Selected Topics in Power Electronics, (2020). DOI: 10.1109/JESTPE.2020.3006013.
https://ieeexplore.ieee.org/abstract/document/9129804

A. Moulay, T. Djerafi, "Oversized Substrate-Integrated Waveguide for High-Power Millimeter-Wave Systems," in IEEE Transactions on Plasma Science,(2020). DOI: 10.1109/TPS.2020.3001828.
https://ieeexplore.ieee.org/abstract/document/9123924

Jin-Hai Sun, Shao-Hua Zhang, Xu-Tao Zhang, et al., "Study on the Dispersion Characteristics of Terahertz Waves in Helical Waveguides," Chinese Physics B, (2020). DOI: 10.1088/1674-1056/aba098.
https://iopscience.iop.org/article/10.1088/1674-1056/aba098/meta

H. Li, J. Wang, Y. Yao, Y. Luo, "Investigation on Ku-Band Dual-State Gyro-TWT," in IEEE Transactions on Plasma Science, (2020). DOI: 10.1109/TPS.2020.3001199.
https://ieeexplore.ieee.org/abstract/document/9119876

N. Kumar, A. Bera, "RF Behavior of a Coaxial Interaction Structure for 0.24-THz, 2-MW Gyrotron," in IEEE Transactions on Electron Devices, (2020). DOI: 10.1109/TED.2020.3000975.
https://ieeexplore.ieee.org/abstract/document/9122468

Lu Xueying, Picard Julian F., Shapiro Michael A., Mastovsky Ivan, Temkin Richard J., et al., "Coherent high-power RF wakefield generation by electron bunch trains in a metamaterial structure,"Applied Physics Letters, vol. 116, n. 26 (2020) 264102. DOI:10.1063/5.0012671.
https://aip.scitation.org/doi/10.1063/5.0012671

Nusinovich G. S., Chen X., Dumbrajs O., Xiao H., Han, X., "Zones of soft and hard self-excitation in gyrotrons: Generalized approach," Physics of Plasmas, vil. 27, n. 7 (2020) 073103. DOI: 10.1063/5.0010377.
https://aip.scitation.org/doi/full/10.1063/5.0010377

Cherkasova, O.P., Serdyukov, D.S., Ratushnyak, A.S. et al. "Effects of Terahertz Radiation on Living Cells: a Review," Opt. Spectrosc., vol. 128 (2020) 855–866. DOI:10.1134/S0030400X20060041.
https://link.springer.com/article/10.1134/S0030400X20060041

Sawant A., Kwak D., Lee I., Chung M., Choi EunMi, "Stand-off radiation detection techniques," Review of Scientific Instruments, vol. 91, n. 7 (2020) 071501. DOI: 10.1063/1.5134088.
https://aip.scitation.org/doi/10.1063/1.5134088

S. Zhang, Q. Xue, X. Wang, K. Wang and D. Zhao, "Analysis of Coaxial Gyrotron Cavity With a Misaligned Insert," in IEEE Transactions on Plasma Science, (2020). DOI:10.1109/TPS.2020.3005593.
https://ieeexplore.ieee.org/abstract/document/9137726

Z. Wang and S. Yu, "The Nonlinear Design and Experiment of a 0.68-THz Second Harmonic Gyrotron," in IEEE Transactions on Plasma Science, (2020). DOI:10.1109/TPS.2020.3004559.
https://ieeexplore.ieee.org/abstract/document/9143130

Jie Huang, Tao Song, Chen Zhang, Wei Wang, Kaichun Zhang, Min Hu, Zhenhua Wu, Renbin Zhong, Jun Zhou, Tao Zhao, Sen Gong, and Diwei Liu, "Theoretical Investigations on Forward-Wave and Backward-Wave Operation of a Frequency-Tunable Gyrotron," in IEEE Transactions on Electron Devices, (2020). DOI: 10.1109/TED.2020.3009960.
https://ieeexplore.ieee.org/abstract/document/9158499

Sandeep Singh, R.M. Mehra, "Review on Modelling of High Power Klystrons," Journal of Critical Reviews, vol. 7, n. 3 (2020) 801-805. DOI:10.31838/jcr.07.03.140.
http://www.jcreview.com/?mno=120979

Othman M. A., Picard J., Schaub S., Dolgashev V.A., Lewis S.M., Neilson J., "Experimental demonstration of externally driven millimeter-wave particle accelerator structure," Applied Physics Letters, vol. 117, n. 7 (2020) 073502. DOI:10.1063/5.0011397.
https://aip.scitation.org/doi/10.1063/5.0011397

V. Kubarev et al., "The Radiation Beamline of Novosibirsk Free Electron Laser Facility Operating in Terahertz, Far-Infrared, and Mid-Infrared Ranges," in IEEE Transactions on Terahertz Science and Technology, (2020). DOI:10.1109/TTHZ.2020.3010046.
https://ieeexplore.ieee.org/document/9143485

S. Han, "Application of a Compact Sub-Terahertz Gyrotron for Nondestructive Inspections," in IEEE Transactions on Plasma Science, vol. 48, n. 9 (2020) 3238 - 3245. DOI:10.1109/TPS.2020.3011806.
https://ieeexplore.ieee.org/abstract/document/9160968

T. Song et al., "Effects of the Magnetic Field Taper on a Continuously Frequency-Tunable Gyrotron," in IEEE Transactions on Electron Devices, vol. 67, n. 9 (2020) 3815-3820. DOI:10.1109/TED.2020.3010182.
https://ieeexplore.ieee.org/abstract/document/9154514

S. Hou, "Simulation of Multimode Competition of a Coaxial Cavity Gyrotron With Multiple Electron Beams," in IEEE Transactions on Plasma Science,(2020). DOI:10.1109/TPS.2020.3013412.
https://ieeexplore.ieee.org/abstract/document/9165950

D. Damyanov, A. Batra, B. Friederich, T. Kaiser, T. Schultze and J. C. Balzer, "High-Resolution Long-Range THz Imaging for Tunable Continuous-Wave Systems," in IEEE Access, vol. 8 (2020) 151997-152007. DOI:10.1109/ACCESS.2020.3017821.
https://ieeexplore.ieee.org/abstract/document/9171245

Meyers V., et al, "p-type conductivity and damage recovery in implanted GaN annealed by rapid gyrotron microwave annealing," Journal of Applied Physics, vol. 128, n. 8 (2020)085701. DOI:10.1063/5.0016358.
https://aip.scitation.org/doi/full/10.1063/5.0016358

G. Ma et al., "Design of Cavity for Quasi-Optical Gyrotron Step-Tunable Across Multiband," in IEEE Transactions on Electron Devices, (2020). DOI: 10.1109/TED.2020.3012522.
https://ieeexplore.ieee.org/abstract/document/9165804

Darr A.M., Darr C.R., Garner A. L., “Theoretical assessment of transitions across thermionic, field, and space-charge-limited emission,” Physical Review Research, vol. 2, n. 3 (2020) 033137. DOI: 10.1103/PhysRevResearch.2.033137.
https://journals.aps.org/prresearch/abstract/10.1103/PhysRevResearch.2.033137

L. Afsah-Hejri, E. Akbari, A. Toudeshki, T. Homayouni, A. Alizadeh, R. Ehsani, "Terahertz spectroscopy and imaging: A review on agricultural applications," Computers and Electronics in Agriculture,vol. 177 (2020) 105628. DOI:10.1016/j.compag.2020.105628.
http://www.sciencedirect.com/science/article/pii/S0168169919318204

P. Wang, Z. Deng, Z. Wang, X. Han, et al., "Numerical and Experimental Verification of a Pulsed Magnet for an 800-GHz Gyrotron," in IEEE Transactions on Electron Devices, (2020). DOI:10.1109/TED.2020.3018098.
https://ieeexplore.ieee.org/document/9184245

Louksha O.I., Trofimov P.A., “Development of a Collector with Multistage Recuperation for Gyrotron,” J. Commun. Technol. Electron., vol. 65 (2020) 950–955. DOI:10.1134/S1064226920080082.
https://link.springer.com/article/10.1134/S1064226920080082

Hsin-Yu Yao, Tsun-Hsu Chang, "Time-domain analysis of superluminal effect for one-dimensional Fabry-Pérot cavity,” Chinese Journal of Physics, (2020). DOI:10.1016/j.cjph.2020.08.020.
http://www.sciencedirect.com/science/article/pii/S0577907320302215

W. Wang, G. Liu, W. Jiang, Y. Pu, J. Wang and Y. Luo, "Design and Measurement of a Broadband Compact TE_{11} Mode Input Coupler for an X-Band Gyrotron Traveling Wave Tube," in IEEE Transactions on Microwave Theory and Techniques, vol. 67, n. 10 (2020) 4460 - 4466. DOI: 10.1109/TMTT.2020.3016305.
https://ieeexplore.ieee.org/abstract/document/9177330

X. Li, D. Zhao, Q. Xue and Y. Xiang, "Analysis of the Combined Cyclotron and Cherenkov Resonances in Metallic Grating Structures," in IEEE Transactions on Plasma Science, (2020). DOI:10.1109/TPS.2020.3015201.
https://ieeexplore.ieee.org/abstract/document/9170605

Qiang Zheng, Zhenghu Huang, Yafen Shang, Man Liu, Yanzhuo Li, Yong Luo, Hao Fu, “Single-phase (Ba,Ca)2ScAlO5 impregnant for dispenser cathodes with enhanced thermionic emission performance,” Ceramics International, (2020). DOI:10.1016/j.ceramint.2020.08.279.
http://www.sciencedirect.com/science/article/pii/S027288422032681X

Farhat M., Amer A.M., Cunningham V.B., Salama K.N., “Numerical modeling for terahertz testing of non-metallic pipes,” AIP Advances, vol. 10, n. 9 (2020) 095112. DOI:10.1063/5.0017327.
https://aip.scitation.org/doi/full/10.1063/5.0017327

Hong J., Park J.Y., Kim S.J. et al., “A Study on the Performance of the Cryostat System for the 28-GHz Electron Cyclotron Resonance Ion Source at the Korea Basic Science Institute,” J. Korean Phys. Soc. vol. 77 (2020) 404–408. DOI:10.3938/jkps.77.404.
https://link.springer.com/article/10.3938/jkps.77.404

Wu Xiaoling, Chen Changhua, Teng Yan, Li Xiaoze, Tan Weibing, Shi Yanchao, Zhu Xiaoxin, Zhang Ligang, "A compact coaxial cusped periodic permanent magnet for a coaxial relativistic Čerenkov generator," Physics of Plasmas, vol. 27, n. 8 (2020) 083104. DOI: 10.1063/5.0014102.
https://aip.scitation.org/doi/abs/10.1063/5.0014102

C. Zhang et al., "Theoretical Analysis and PIC Simulation of a 140-GHz Double Confocal Waveguide Gyro-TWA," in IEEE Transactions on Electron Devices, vol. 67, n. 10 (2020) 4453-445 DOI: 10.1109/TED.2020.3017575.
https://ieeexplore.ieee.org/abstract/document/9186807

Meshcheryakov A.I., Vafin I.Y., Grishina, I.A., “Longitudinal Electric Field in the Ohmic and Electron Cyclotron Resonance Regimes of Plasma Heating at the L-2M Stellarator,” Instrum Exp Tech, vol. 63 (2020) 689–694. DOI:10.1134/S002044122005019X.
https://link.springer.com/article/10.1134/S002044122005019X

A. Mercy Latha, S. K. Ghosh, “A comprehensive review of depressed collectors of slow-wave devices,” Journal of Electromagnetic Waves and Applications, (2020). DOI: 10.1080/09205071.2020.1823895.
https://www.tandfonline.com/doi/abs/10.1080/09205071.2020.1823895?journalCode=tewa20

Wong H., Wang K.X., Huitema L. et al., “Active meta polarizer for terahertz frequencies.,” Sci Rep, vol. 10 (2020) 15382. DOI:10.1038/s41598-020-71990-z.
https://www.nature.com/articles/s41598-020-71990-z

Lu D., Fu W., Guan X., YangT., Zhang C., Chen C., Han M., Yan Y.,”Ultra-High Velocity Ratio in Magnetron Injection Guns for Low-Voltage Compact Gyrotrons,” Electronics , vol. 9 (2020) 1587.
https://www.mdpi.com/2079-9292/9/10/1587

Zhang L., Nix, L., Cross, A., “Magnetron injection gun for high-power gyroklystron,” IEEE Transactions on Electron Devices, (2020) . (In Press)
https://strathprints.strath.ac.uk/73952/

Passarelli A., Bartosik H., Rumolo G., Vaccaro V.G., Masullo M.R., Koral C., Andreone A., Boine-Frankenheim O., "Sub-THz EM characterization of coated material,” CERN Yellow Rep. Conf. Proc. (2020). DOI:10.23732/CYRCP-2020-007.83.
https://inspirehep.net/literature/1819963

Habib M.A., Reyes-Vera E., Villegas-Aristizabal J., Anower M.S., “Numerical Modeling of a Rectangular Hollow-Core Waveguide for the Detection of Fuel Adulteration in Terahertz Region,” Fibers, vol. 8, n.10 (2020) 63. DOI: 10.3390/fib8100063.
https://www.mdpi.com/2079-6439/8/10/63

Zhang Ch., Fu W., Yan Y., "Study on a gyrotron quasi-optical mode converter for terahertz imaging," Journal of Electromagnetic Waves and Applications, (2020). DOI:10.1080/09205071.2020.1828186.
https://www.tandfonline.com/doi/abs/10.1080/09205071.2020.1828186?journalCode=tewa20

G. Jaworski, A. Francik, M. Nowak, K. Nowak, "Review of Experimental Verification Methods of Gyrotron Quasi-optical Mode Converters," Journal of Communication and Information Technology, vol. 3 (2020) 75-85. DOI: 10.26636/jtit.2020.141320.
https://www.itl.waw.pl/czasopisma/JTIT/2020/3/75.pdf

Artem'ev, K.V., Batanov, G.M., Berezhetskaya, N.K. et al., "Parameters of a Subthreshold Microwave Discharge in Air and Carbon Dioxide as a Function of Microwave Field at Different Gas Pressures," Plasma Phys. Rep., vol. 46 (2020) 927–935. DOI:10.1134/S1063780X20090019.
https://link.springer.com/article/10.1134/S1063780X20090019

M.V. Swati and P.K. Jain, "Systematic Time-Dependent, Multimode Simulation Study of a Ka-Band, Three-Cavity Second-Harmonic Gyroklystron Amplifier," in IEEE Transactions on Plasma Science, vol. 48, n. 10 (2020) 3558-3564. DOI:10.1109/TPS.2020.3019971.
https://ieeexplore.ieee.org/abstract/document/9189778

A.K. Singh, S.K. Shukla, M. Ravi and R. K. Barik, "A Review of Electron Emitters for High-Power and High-Frequency Vacuum Electron Devices," in IEEE Transactions on Plasma Science, vol. 48, n. 10 (2020) 3446-3454. DOI:10.1109/TPS.2020.3011285.
https://ieeexplore.ieee.org/abstract/document/9200465

Roquais J.M., Vancil B., Green M. (2020) Review on Impregnated and Reservoir Ba Dispenser Cathodes. In: Gaertner G., Knapp W., Forbes R.G. (Eds.) Modern Developments in Vacuum Electron Sources. Topics in Applied Physics, vol 135. Springer, Cham. DOI:10.1007/978-3-030-47291-7_2.
https://link.springer.com/chapter/10.1007/978-3-030-47291-7_2

L. Wang, X. Niu, Y. Liu and S. Chen, "High-Order Rotating Mode Generator Using Quasi-Optical Techniques," in IEEE Transactions on Plasma Science, vol. 48, n. 10 (2020) 3495-3500 DOI:10.1109/TPS.2020.3020953.
https://ieeexplore.ieee.org/abstract/document/9204752

C Patents

Sheet beam electron gun using axially-symmetric spherical cathode
Inventors: David R. WhaleyAndrew P. Zubyk
US Patent: US10672583B1
Date of publication: 06/02/2020
https://patents.google.com/patent/US10672583B1/en

Microwave plasma sterilization system and applicator thereof
Inventors: Hancock, Christopher Paul (Bristol, GB)
US Patent: 20200171180
Date of publication: 06/04/2020
http://www.freepatentsonline.com/y2020/0171180.html

Pulsed electron paramagnetic resonance spectrometer
Inventors: Zongquan ZhouPeiyun LiChao LiuXiao LiuChuanfeng LiGuangcan Guo
US Patent: US20200182955A1
Date of publication: 06/11/2020
https://patents.google.com/patent/US20200182955A1/en

Compact standing-wave linear accelerator structure
Inventor: Eiji Tanabe
US Patent: US20200187345A1
Date of publication: 06/11/2020
https://patents.google.com/patent/US20200187345A1/en

NEW BOOKS

Riadh Habash, BioElectroMagnetics Human Safety and Biomedical Applications, 2nd Edition (Published 4 May 2020, Boca Raton, CRC Press) 540 pages. DOI:10.1201/9780429184093. eBook ISBN9780429184093.
https://www.taylorfrancis.com/books/9780429184093

Generation and Application of High Power Microwaves, Edited by R.A Cairns, A.D.R. Phelps, (CRC Press, 2020) 351 pages. ISBN 1000157180, 9781000157185.
https://www.routledge.com/Generation-and-Application-of-High-Power-Microwaves/Cairns-Phelps/p/book/9781003063070

Igor Vintizenko, Linear Induction Accelerators for High-Power Microwave Devices (CRC Press, 2020) 351 pages. ISBN 9780367571382.
https://www.routledge.com/Linear-Induction-Accelerators-for-High-Power-Microwave-Devices/Vintizenko/p/book/9780367571382

Jae-Sung Rieh, Introduction to Terahertz Electronics, (Springer International Publishing, 2021). eBook ISBN 978-3-030-51842-4. Hardcover ISBN 978-3-030-51841-7DOI:10.1007/978-3-030-51842-4.
https://www.springer.com/gp/book/9783030518417

Georg Gaertner, Wolfram Knapp, Richard G. Forbes (Eds.), Modern Developments in Vacuum Electron Sources. Topics in Applied Physics, vol 135, (Springer, 2020). DOI:10.1007/978-3-030-47291-7. Print ISBN 978-3-030-47290-0; Online ISBN 978-3-030-47291-7.
https://link.springer.com/book/10.1007/978-3-030-47291-7