NEWSLETTER

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

February 2020 № 14

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:

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SHORT INVITED PAPER

Control of sub-terahertz gyrotron frequency by modulation of the anode voltage

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Gyrotrons are well known as the powerful radiation sources in sub-THz and THz frequency ranges. Together with power and efficiency, for some applications, for instance, those associated with spectroscopy and diagnostics of various media, a CW oscillation regime with narrow radiation spectrum and smooth wideband oscillation frequency tuning are highly sought for. In this case, the gyrotron output power would still be several orders higher than the power of classical BWOs and solid-state oscillators thus uncovering brand new possibilities for research. Thus, in order to satisfy the growing demands of modern applications, it is necessary to pay more attention to the methods of frequency control in gyrotrons.

The active methods of frequency control include several relatively slow methods like variation of magnetic field, cavity temperature, and cavity radii as well as faster methods of voltage variation on the electrodes the electron-optic system, namely accelerating voltage, cavity voltage (in the gyrotrons with electron energy recovery) or modulation-anode voltage in triode-type magnetron injection guns. The latter seems to be most reasonable since the voltage is varied at the isolated electrode, the capacitance of which is relatively small with respect to other electrodes of the electron-optical system and is usually about tens of picofarad. Moreover, the mod-anode current is low and so the corresponding power supply can be small, simple and cheap. A number of experiments (including FIR UF and IAP RAS groups) with gyrotrons of different frequencies demonstrated its simplicity, reliability, modulation frequency up to hundreds of kHz and paved the way for record frequency stability of the gyrotron. The objective of this report is to compare theoretical calculations with experimental results in order to draw a conclusion about the existence of a theory that can accurately describe the process of frequency control by variation of modulation-anode voltage.

The theory of frequency pulling in gyrotrons is based on the basic theory developed by L. A. Weinstein with V. A. Solntsev, who considered the excitation of oscillations in a resonator excited by an electron beam with the current density $\vec{j}(t) = \mathrm{Re}\left\{\vec{j}(\omega)e^{i\omega t}\right\}$ and introduced the complex power of beam-wave interaction $P = P_{act} + iP_{im}$. In terms of components of such complex power, equations describing the stationary oscillations in any resonator can be reduced to the equation describing the balance of active powers and the equation describing the reactive power. The first one determines the amplitude of oscillations excited by an electron beam in a resonator with a given Q-factor; the second one (describing the balance of reactive powers) determines the shift of the oscillation frequency with respect to the real part of the complex eigenfrequency of a cold cavity $\omega_s = \omega'_s - i\omega'_s / 2Q_s$ (s is the mode index), i.e. the frequency pulling effect. In notations adopted in the gyrotron theory, the same effects can be described by using the susceptibility of an electron beam to the electromagnetic field of a resonator $\chi = \chi' + i\chi''$. The relation between this susceptibility and the complex power can be given as:

$$I\chi = \frac{iQ}{\omega'_s W} P \tag{1}$$

In (1), I is the normalized beam current parameter, W is the microwave energy stored in a resonator. In the notations adopted in the gyrotron theory, corresponding balance equations can be given as:

$$I\chi'' = 1 \tag{2}$$

$$\frac{\omega - \omega'_s}{\omega'_s / 2Q_s} = -I\chi' \tag{3}$$

Note that in the framework of this theory the susceptibility χ depends on three dimensionless parameters only: the cyclotron resonance mismatch Δ, the normalized length of the interaction space μ and the normalized amplitude of oscillations in the resonator F; the latter, in accordance with Eq. (2) depends, in turn, on the beam current parameter I. For our treatment, it is important that all three parameters depend on the components (orbital and axial) of the electron velocity. In particular, and possibly the most important, is the dependence in the transit angle $\theta = (\omega - s\Omega_0)(L / v_z)$, which is the product of the mismatch and the normalized interaction length $\theta = \Delta\mu$. Therefore, the variation in the modulation-anode voltage, which is considered below, causes the variation in the transit angle that has a strong effect on the electron bunching and resulting gyrotron output frequency and power.

For the method of modulation-anode voltage control, the electron energy, which is determined by the accelerating voltage (cathode-cavity potential), remains constant, and a change of the mod-anode potential affects only on an electrons pitch-factor g (relation between orbital and axial velocities of electrons). Therefore, in order to calculate the frequency shift, it is important to know the components of electron velocity with high enough accuracy and utilize the adequate model of beam-wave interaction (the one that takes into account the greatest number of effects and at the same time with reasonable calculation time). The authors use a "classical" approach – divide the problem into two sub-problems that can be solved independently using relatively simple models for which the computation time is orders of magnitude less than for the packages described above. The first problem is the calculation of the parameters of the electron beam formed in the axially symmetric magnetron-injection gun with a varying mod-anode voltage and the second is the calculation of the interaction of the resulting electron beam with the electromagnetic field in the gyrotron cavity in a self-consistent model of a gyrotron with non-fixed field structure. The numerical simulation and subsequent comparison with the experiment was made for a real tube with a frequency of 263 GHz and an output power of 1 kW, which was developed at IAP RAS.

The calculation of electron-wave interaction was made by using the self-consistent steady-state single-mode equations. The model with a non-fixed longitudinal RF-field structure *f(z)* takes into account the electron velocity and guiding center spread, non-uniform magnetic field and the real resonator profile. The transverse drift of electron orbit centers, RF space charge and re-radiation of the operating mode into modes with different radial indexes were not taken into account since at optimal gyrotron parameters their influence is negligibly small. The calculated value of the pitch-factor is substituted into the energy conservation law and the corresponding values of electrons oscillatory $p_\perp = p_{\perp 0}$ and longitudinal $p_z = p_{z0}$ momentums at the entrance of the cavity were obtained. These values are then used as initial ones for microwave field calculation in the presence of electron beam. As a result, the generation frequency and total gyrotron efficiency for a set of considered values ΔU_a and magnetic fields were found. The calculated dependencies of the operating gyrotron frequency and efficiency on the mod-anode voltage variation and magnetic field in the cavity region (cyclotron resonance mismatch) are shown in Fig.1, 2.

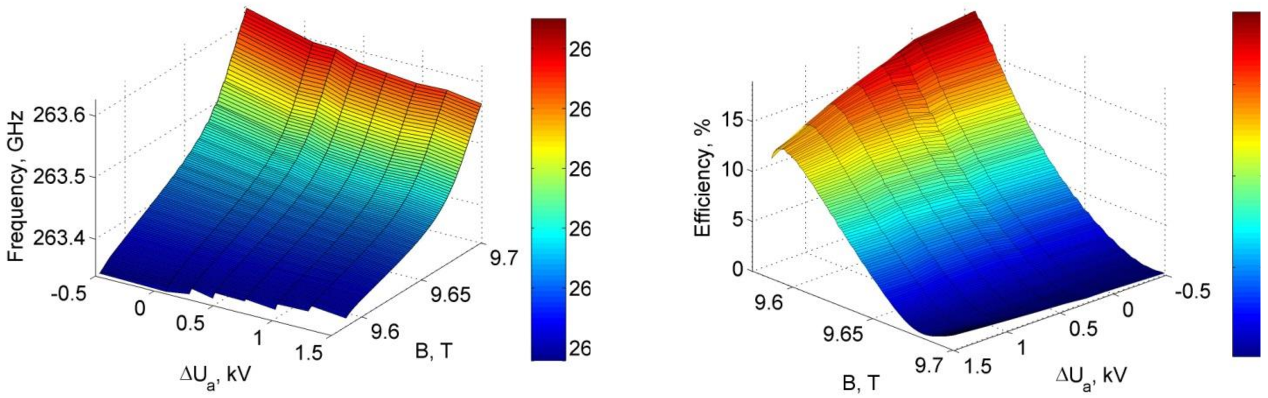

Fig. 1 and 2 Calculated dependencies of the gyrotron operating frequency (left) and gyrotron efficiency (right) on the magnetic field and anode voltage.

It should be noted that for regimes with high interaction efficiency (in Fig.2 this region corresponds to *B* close to 9.6 T) the influence of beam pitch factor on the frequency of microwave radiation is rather low ($\Delta f / \Delta U_a$ = 1.3 MHz/kV), while the overall efficiency of the gyrotron varies quite a lot ($\Delta\eta / \Delta U_a = 5.1$ %/kV). The highest sensitivity of frequency to the variation of mod-anode potential $\Delta f / \Delta U_a$ = 30 MHz/kV is predicted at high magnetic fields (in Fig. 1 this region corresponds to *B* close to 9.7 T), for regimes with low interaction efficiency. As it follows from numerical simulation, the optimal regime for spectroscopic gyrotron would be not the maximum efficiency point, but the middle of the generation zone, since it offers greater frequency tuning and less output power modulation, as well as a reasonable level of output power about 100 watts.

To verify the obtained results, measurements of the radiation frequency versus modulation-anode voltage were performed. Keysight N9010A spectrum analyzer with a harmonic mixer in the range 230-320 GHz (produced in Research Institute of Semiconductor Devices) was used (Fig. 3). The experiments were performed at the accelerating voltage of 15 kV and a beam current of 0.1 A to comply with the numerical simulation conditions. The experiment confirmed the dependence of frequency sweep bandwidth on the operating regime of the gyrotron with experimentally measured sensitivity of the frequency to the modulation-anode potential variation ranging from 5 to 30 MHz/kV for minimal and maximal operating magnetic fields. Acquired dependencies of gyrotron frequency on the mod-anode voltage are in a good agreement with the results of the numerical simulation. A comparison of the obtained experimental dependency with numerical calculations for a fixed magnetic field equal to 9.68 T is presented in Fig. 4. The observed discrepancy between theoretical predictions and experiment $\delta\omega/\omega$ values is about $3{\cdot}10^{-5}$, which is an order of magnitude smaller than in previous work (I.Antakov, et al., *Int. J. Infrared Millimeter Waves*, **14**, 5, 1001–1015, 1993).

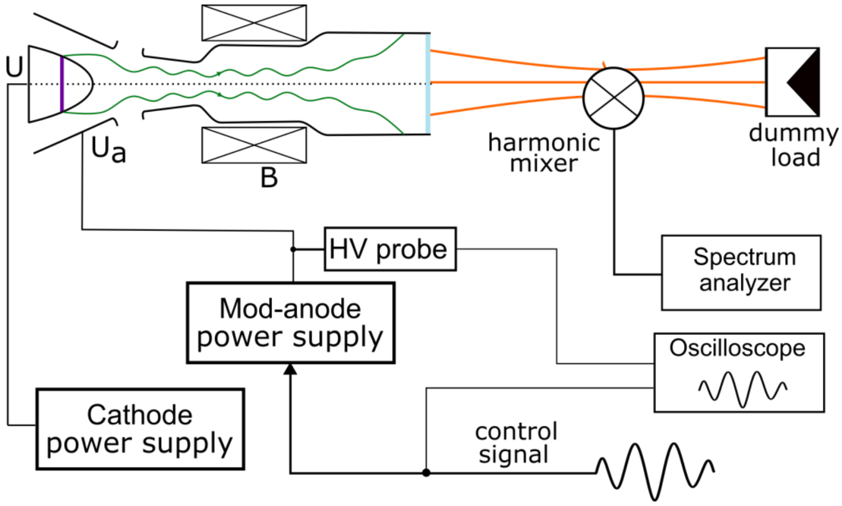

Fig.3 Scheme of the gyrotron, power supply connections and measurement system

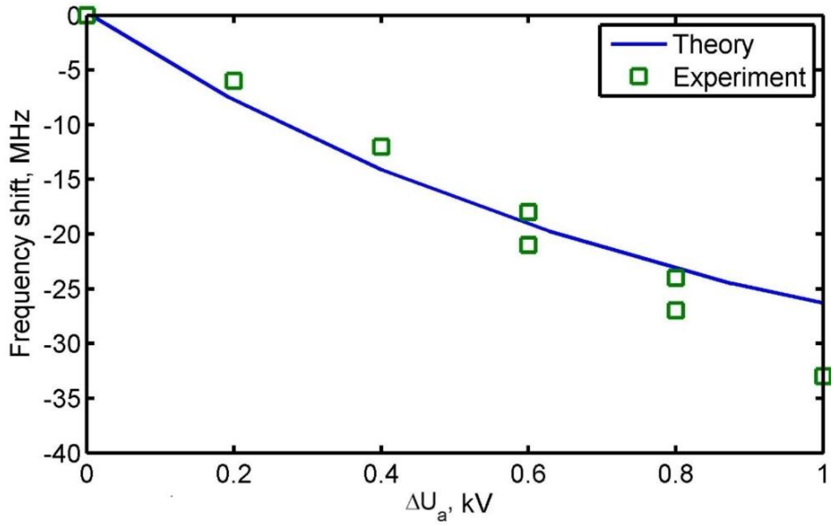

Fig.4. Comparison of the theoretical and experimental results for frequency shift caused by the anode voltage variation for a fixed magnetic field (initial value of mod-anode voltage U_a = 13 kV, B = 9.68 T).

The results of numerical simulation of the gyrotron frequency and efficiency in the simple two-step scheme are in agreement with the experimentally observed dependencies of the frequency shift on the modulation-anode voltage variation and the generation regime. Observed discrepancy between theoretical predictions and experimental results is significantly smaller than in earlier works. It proves the credibility of the simple theoretical approach to calculation of the gyrotron frequency and power as functions of technical parameters, especially anode voltage, and allows the use of the described method for the development of frequency control systems for modern high-frequency gyrotrons.

More detail: A.P. Fokin, at al. Rev. Sci. Instrum. **90**, 124705 (2019); https://doi.org/10.1063/1.5132831.

FORTHCOMING EVENTS

IRMMW-THz 2020
Buffalo

September 13–18, 2020

45th International Conference on Infrared, Millimeter, and Terahertz Waves

Buffalo Niagara Convention Center
Buffalo, New York, USA

Conference Co-Chairs
Andrea Markelz University at Buffalo, USA
Erik Einarsson University at Buffalo, USA

Technical Program Chair
Frank Hegmann University of Alberta, Canada

Local Organizing Committee
Priya Banerjee University at Buffalo, USA
Luis Velarde University at Buffalo, USA
John Cerne University at Buffalo, USA
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11th International Workshop
MW 2020

Strong Microwaves and Terahertz Waves: Sources and Applications
July 5–10, 2020
Nizhny Novgorod, Russia

The Institute of Applied Physics of Russian Academy of Sciences announces that the 11th International Workshop "Strong Microwaves and Terahertz Waves: Sources and Applications" will be held on July 5–10, 2020 on a river cruise starting and ending in Nizhny Novgorod, Russia.

The side events at the workshop include the 32nd Joint Russian-German Meeting on ECRH and Gyrotrons and a school on high power microwave vacuum electronics for young scientists and PhD students. Traditionally, the workshop is held aboard a comfortable cruise riverboat. This provides a unique opportunity for the participants to take a closer look at Russian history and culture. A sightseeing program on the route, a special program for accompanying persons, and a set of social events are scheduled.

For more detail visit the website of the Workshop.

For more conferences to be held in 2020 visit the preceding issue Newsletter #13.

PERSONALIA

Happy 55th Birthday to Professor Mikhail Glyavin

M. Glyavin was born in Nizhny Novgorod, Russia, on 14 February 1965. He received the Ph.D. degree and Dr. Sci. degree in physics from the Institute of Applied Physics, Russian Academy of Sciences, in 1999 and 2009, respectively. After graduation of the Politechnical Institute, Gorky, USSR, in 1988, he joined the Institute of Applied Physics of the Russian Academy of Sciences (IAP-RAS, where he is engaged in the development of high-power gyrotrons for nuclear fusion and other applications. His dissertation was focused on studies of gyrotrons, development of gyrotron based systems for technological applications and more specifically on methods for increasing the gyrotron efficiency and mastering of THz band. From 1999 up to now, at intervals, he was a Visiting Professor at the FIR FU Center, Fukui, Japan. Currently, he is a Deputy Director of Research at IAP-RAS, an Associate Professor with Nizhny Novgorod State University, Nizhny Novgorod, Russia, and a Head of the Laboratory of microwave treatment of materials at IAP-RAS.

M. Glyavin is a leading specialist and worldwide renowned scientist in the fields of radiophysics and physical electronics. His research interests are in the field of the theoretical and experimental investigations of various gyro-devices, including gyrotrons and their application to materials processing and diagnostic of various media. Among his remarkable results are the following: a study of the processes of interaction of helical electron flows with eigenmodes of various electrodynamic systems and the proposal of new principles and design of various gyro-devices; development of a series of technological complexes for microwave processing of materials with increased efficiency and functionality; the formation of the foundations of a new promising direction - powerful sources of radiation in the terahertz frequency range. Under his leadership and with his direct participation, record-breaking frequencies, powers and spectral characteristics of the radiation of gyro devices were achieved both in pulsed and continuous modes of generation; pioneering work on initiating a localized gas discharge, experiments on gas spectroscopy with record sensitivity were performed.

M. Glyavin conducts teaching work, supervising graduate students and students, and lecturing at the University of Nizhniy Novgorod N.I. Lobachevsky. He manages the collaborative research with the Research Center for development of the Far-Infrared Region at the University of Fukui (FIR UF) in Japan (FIR FU, Fukui, Japan), and the University of Maryland in the US. He is an active contributor to the research carried out in the framework of the International Consortium for Development of High-Power THz Science and Technology.

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 October 2019, i.e. after issuing the previous Newsletter #13. 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

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Microwave heating system having improved frequency scanning and heating methods
Inventors: Jung Hyeong HA, Seoul (KR); Sung - Hun SIM, Seoul (KR); Hyo Jin AN, Seoul (KR); Jongseong JI, Seoul (KR); Yun Byung CHAE , Seoul (KR)
US Patent: US 2019 / 0313488 A1
Date of publication: 10.10.2019

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System and method for launching guided electromagnetic waves with impedance matching
Inventor: Harold Lee Rappaport
US Patent: US10446935B1
Date of publication: 15.10.2019
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Charged particle beam device, multi-beam blanker for a charged particle beam device, and method for operating a charged particle beam device
Inventors: Benjamin John Cook, Dieter Winkler
US Patent: US10446935B1
Date of publication: 19.11.2019
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Device with configurable reflector for transmitting or receiving electromagnetic waves
Inventors: Paul Shala Henry, Robert Bennett, Donald J. Barnickel, Giovanni Vannucci, Farhad Barzegar, Irwin Gerszberg, Thomas M. Willis, III, Bruce E. Stuckman
US Patent: US10523269B1
Date of publication: 31.12.2019
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Apparatus and method for guided wave communications using an absorber
Inventors: Paul Shala, Henry Giovanni, Vannucci Thomas M. Willis, III
US Patent: US20190305399A1
Date of publication: 21.01.2020
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Robust and precise synchronization of microwave oscillators to a laser oscillator in pulsed electron beam devices
Inventors: Martin Otto, Bradley Siwick
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NEWS FROM THE NET (OUR BROADER HORIZONS)

Powerful CW Sub-THz Large Orbit Gyrotron (LOG) for NMR spectroscopy

On 23 January 2020, the site *Scientific Russia* published an article that describes a new Large Orbit Gyrotron (LOG) developed at the Institute of Applied Physics of the Russian Academy of Sciences (IAP-RAS). This device has demonstrated a stable generation in a CW regime at frequencies of 0.39 and 0.26 THz and output powers of 0.4 and 0.9 kW, respectively. The well-known advantages of the LOG are high mode selectivity (since only cavity modes with an azimuthal index that is equal to the harmonic number of the cyclotron resonance can be excited effectively) and an inherent high-harmonic operation that reduces the necessary intensity of the magnetic field inversely proportionally to the harmonic number. In contrast to the conventional gyrotrons that utilize magnetron injection guns (MIG) that form helical electron beams (in which the individual electron orbits are helices following the magnetic field lines), the LOGs utilize electron-optical systems (EOS) that produce axis-encircling (aka uni-axial) electron beams. In the latter case, the electrons gyrate around the axis of symmetry on circles with larger Larmor radius (comparable to the radius of the resonant cavity) and hence the name – Large Orbit Gyrotron. These two configurations are illustrated in Fig. 1.

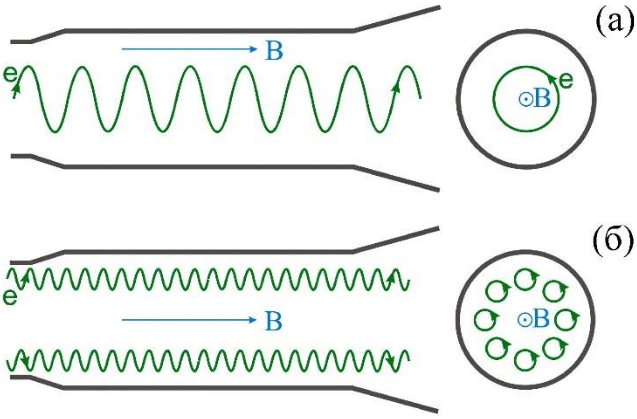

Fig. 1 Resonant structure of LOG with axis-encircling electron beam (a) and a conventional gyrotron with poly-axial (helical) electron beam (b). Image *courtesy Scientific Russia*.

Currently, most of the DNMR-DNP spectrometers utilize radiation sources operating at frequencies of 0.263, 0.395 and 0.527 THz. Such are, for example, the devices developed by Bruker BioSpin company in collaboration with CPI (USA). Wave beams with the mentioned frequencies are delivered by gyrotrons operating at second harmonics of the cyclotron resonance and having superconducting magnets with maximum intensities of 5, 7, and 10 T, respectively. The concept of LOG allows to produce radiation at these three frequencies using the same EOS and collector and changing only the cavity (and therefore the operating mode) and the output system, while the electron-optical system and the collector remain the same. The new LOG developed at IAP-RAS is built using one 5 T cryomagnet and can operate selectively at the 2nd, 3rd and 4th cyclotron harmonics. For the first time in the world, CW operation of LOG has been demonstrated at a frequency of 0.394 THz at the 3rd harmonic of the cyclotron frequency (Fig. 2) operating at relatively low electron energy (30 keV) and a weak magnetic field (about 5 T).

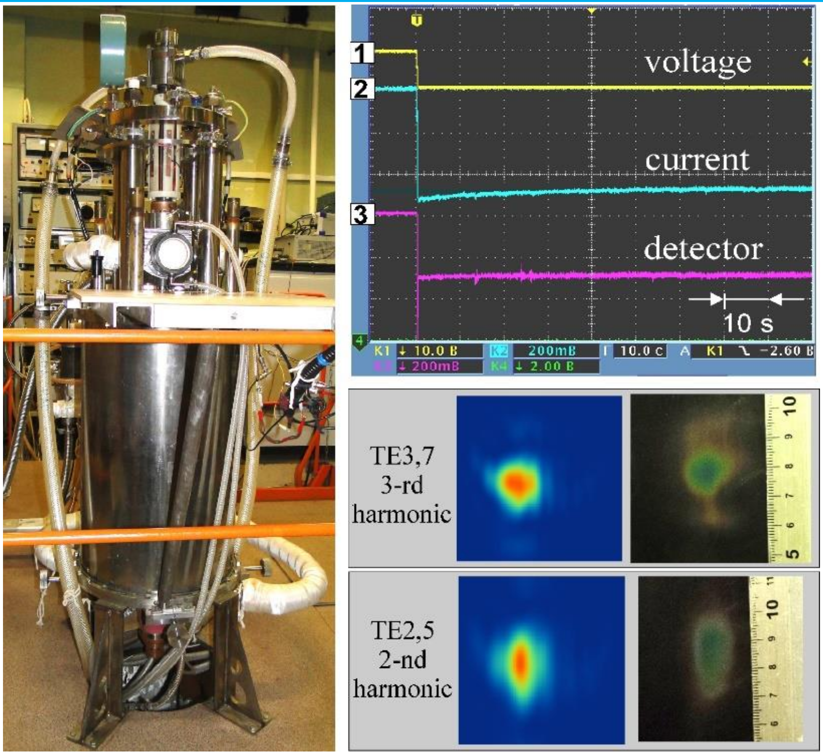

Fig. 2 Photo of the CW LOG (left panel), oscillograms of the signals observed at the moment of the startup and during the first one and a half minutes of operation (upper right panel), and comparison of calculated and measured intensities of the output beam (lower right panel). Image courtesy *Scientific Russia*.

For more details see the original paper: 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. (link)

A new approach for injecting powerful microwaves into fusion plasma

Powerful microwave radiation produced by gyrotrons is used for electron cyclotron resonance heating (ECRH) and current drive (ECCD) of magnetically confined plasma in fusion reactors (e.g. tokamaks). For the first time in DIII-D tokamak, the researchers from the National Fusion Facility in San Diego have measured significantly higher off-axis ECCD efficiency (more than twice higher than that obtained previously) using a novel top launch geometry. It is expected that such a breakthrough will facilitate the development of more efficient and compact fusion power plants.

For more detail please visit the following sources:

1. Higher Off-Axis Electron Cyclotron Current Drive Via 'Top Launch (link)
2. Taking new angle to enable more efficient, compact fusion power plants (link)
3. Top launch ECCD enabling higher off-axis current drive for steady-state operation of burning plasma tokamaks (link)

World record acceleration: Zero to 7.8 billion electron volts in 8 inches

An article published on 21 October 2019 in *PhysOrg* of the American Physical Society reports that a team at Berkeley Lab's BELLA Center doubled the previous world record for energy produced by laser plasma accelerators, generating electron beams with energies up to 7.8 billion electron volts (GeV) in an 8-inch-long plasma (20 cm). This would require about 300 feet (91 m) using conventional technology. For more detail see the original paper: J. Gonsalves et al, "Petawatt Laser Guiding and Electron Beam Acceleration to 8 GeV in a

Laser-Heated Capillary Discharge Waveguide," Phys. Rev. Lett. 122, 084801 (2019). DOI: 10.1103/PhysRevLett.122.084801. (link)

A new way for detection of terahertz electromagnetic waves

A team of physicists at the University of California has discovered an electrical detection method for terahertz electromagnetic waves, which could help miniaturize the detection equipment on microchips and enhance sensitivity according to a paper published in Nature (Li J., Wilson C.B., Cheng R. et al. "Spin current from sub-terahertz-generated antiferromagnetic magnons, *Nature* (2020). DOI:10.1038/s41586-020-1950-4. link). The new method is based on a magnetic resonance phenomenon in antiferromagnetic materials that are ubiquitous and more abundant than ferromagnets. Moreover, many ferromagnets (e.g. iron and cobalt) become antiferromagnetic when oxidized. Such materials are considered very promising for the development of various spin-based nanoscale device applications. In their experiments, the researchers have generated a spin current in an antiferromagnet and detected it electrically by pumping up a magnetic resonance in heterostructures of a uniaxial antiferromagnetic Cr_2O_3 crystal and a heavy metal (Pt or Ta in its β phase) using terahertz radiation with a frequency of 0.24 THz. According to the authors, their findings reveal the unique characteristics of magnon excitations in antiferromagnets and their distinctive roles in spin–charge conversion in the high-frequency regime.

A popular description of this new method and its implications for the electronics is given in an article published in SciTech Daily and another one in *Nano Werk*.

Breakthrough in terahertz waves

Hamamatsu Photonics has succeeded in producing terahertz waves at a wavelength of 450 μm, which is the world's longest wavelength available from a single semiconductor laser operating at room temperature. To achieve this breakthrough, the firm has developed long-wavelength mid-infrared quantum cascade laser, in which it designed the laser structure based on research and analysis results of the terahertz wave generation principle. Results from this research will be useful in applications such as quality testing and non-destructive inspection of drugs and foods containing components that absorb electromagnetic waves in the sub-terahertz range as well as submillimeter astronomy and high-speed and high-capacity communication over short distances. For more detail visit the article presented at the site of Hamamatsu Photonics following the link.

Researchers generate terahertz laser with nitrous oxide (laughing gas)

An article in the *MIT News* reports that researchers from MIT, Harvard University, and the U.S. Army have built a compact device, the size of a shoebox that produces a terahertz laser whose frequency they can tune over a wide range. The device is built from commercial, off-the-shelf parts and is designed to generate terahertz waves by spinning up the energy of molecules in nitrous oxide, or, as it's more commonly known, laughing gas. Nitrous oxide is used to illustrate the broad tunability over 37 lines spanning 0.251 to 0.955 terahertz, each with kilohertz linewidths. The analysis of the researchers shows that laser lines spanning more than 1 terahertz with powers greater than 1 mW are possible from many molecular gases pumped by quantum cascade lasers. For more information see the original paper (Paul Chevalier, et al "Widely tunable compact terahertz gas lasers," *Science,* vol. 366, Issue 6467 (2019) 856-860. DOI:10.1126/science.aay8683) published in the journal *Science*.