NEWSLETTER

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

March 2016 № 2

CONTENT

EDITORIAL: OUR MISSION AND GOALS

The International Consortium for Development of High-Power Terahertz Science and Technology was established in 2015 in order to unite the efforts of thirteen institutions from nine countries for a joint collaborative work in this challenging and actively advancing research area. The participants in our Consortium are among the leaders in the development and investigation of radiation sources operating in a wide band from sub-THz to THz frequencies and their application to many scientific and technological fields. Among them are novel spectroscopic techniques, processing of advanced materials, plasma physics, medical and biological studies, etc. Although each member is focused on one or several key applications all we share common theoretical background and practical experience in such interdisciplinary research. It is believed that this is a firm basis for a successful and fruitful collaboration, which is expected to draw a synergy effect in near future. In fact, the mere establishment of this

Consortium has been made possibly due to our preceding contacts and active collaborations, including these that have been carried out in the previous framework called "Development and application of submillimeter-wave gyrotrons". Now, in the new Consortium the frequency range is extended to the region that spans from sub-THz to THz frequencies. Understanding the importance of the information exchange for our collaboration the FIR UF, which has organized and serves as a managing institution of the Consortium maintains a website (Visit: http://fir.u-fukui.ac.jp/Website_Consortium/) and issues the present Newsletter. We consider both these media as appropriate forums for sharing of information and discussing the latest news and ideas for collaborative research projects.

The first Newsletter was released in December 2015 and it was decided to issue it quarterly. Our intention is to extend gradually both is scope and volume. For this to happen, however, we rely heavily on an active support from the participating research groups and kindly encourage all our Colleagues to submit regularly any relevant information. Since our goal is to save their valuable time and minimize their efforts, there are no special requirements concerning the preparation of manuscripts. The final typesetting and formatting of the materials will be made by the editor of the Newsletter.

We envisage (but are not limited to) the following rubrics:

- Research highlights (annotations) presenting the projects pursued by the members of the Consortium.
- Short regular 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. Post Doc positions, specialization, internship.
- Annotations of books, conference proceedings, software and internet resources. List of the recent scientific publications and conference reports.
- Information and announcements about awards and nominations.
- Short presentations of laboratories and research groups belonging to the participating institutions.

Any idea and suggestion for improvements to both the website and the Newsletter are welcome and would be greatly appreciated.

RESEARCH HIGHLIGHTS

Development of gyrotrons for DNP-NMR spectroscopy at FIR UF

In recent years, NMR spectroscopy with signal enhancement through dynamic nuclear polarization (DNP-NMR) has become one of the most prominent applications, where the gyrotrons are used as CW sources of coherent radiation. Several tubes developed at FIR UF and belonging to the FU CW Series have been designed, optimized, manufactured and used in various DNP-NMR experiments. The first of them, FU CW II, utilizes an 8 T cryo-free superconducting magnet and has an output frequency of 394.6 GHz (second harmonic operation) that corresponds to 600 MHz proton NMR at a magnetic field of about 14 T. An optimized version of this gyrotron (FU CW IIB) is characterized by a high stability of the output power (fluctuations below 0.5% during 18 h) achieved by using PID feedback control. The next radiation source for 200 MHz DNP-NMR spectroscopy is FU CW IV. Its design is based on a 10 T liquid-He free superconducting magnet. A remarkable feature of this tube is the demonstrated continuous tunability in a broad frequency band from 134 GHz to 140 GHz. It has been achieved by changing the magnetic field in the cavity from 4.9 T to 5.2 T and operating as a gyro-BWO on a sequence of high-order axial modes (HOAM). The same technique for continuous frequency tunability has been used also for the gyrotron FU CW VI, which has a 15 T superconducting magnet and has been designed as a radiation source for the 600 MHz DNP-NMR spectrometer of the Institute for Protein Research at Osaka University. Next gyrotron, FU CW VII, can be used for both 300 and 600 MHz DNP-NMR at output frequencies of 200 GHz (fundamental operation) and 400 GHz (second harmonic of the cyclotron resonance), respectively. This tube is step-tunable in a wide range (from 86 to 223 GHz) because many operating modes can be excited by varying the electron beam parameters and the magnetic field.

Since the gyrotrons used for spectroscopic studies have to be embedded in a sophisticated laboratory infrastructure it is desirable to minimize their weight and dimensions. Additionally, like many other applications, the DNP-NMR spectroscopy demands a well- collimated (Gaussian) wave beam with a linear polarization. In order to satisfy these requirements, development of two new clones of the presented series has started recently. Their specifications (CW C and CW G) contain the symbols C (which stands for "compact") and G (which stands for "Gaussian" beam), respectively. For instance, the overall height of FU CW CI is 1.02 m and that of CII is only 0.86 m. FU CW CI has been designed having several applications in mind including 600 MHz DNP-NMR spectroscopy. It utilizes a compact He-free 8 T superconducting magnet and operates at a frequency of 395 GHz with an output power of 120 W.

The gyrotrons of the CW G series have internal (build-in) mode converter and deliver a Gaussian-like beam with almost circular cross section. Some of them are designed and optimized especially as radiation sources for 600 MHz (FU CW GII at 395 GHz) and 700 MHz (FU CW GVI, and GVIA at 460 GHz), respectively. At Osaka University, where these gyrotrons are installed a slightly different nomenclature is used. According to it, FU CW VI and VIA are named FU CW GO-1 and GO-II, where "GO" indicates that the tube delivers an optimized Gaussian output beam.

Some of the gyrotrons for DNP-NMR spectroscopy developed recently are shown in the following collage.

More details about their operational performance can be found in the following recent publications:

[1] Glyavin M.Y., Idehara T., Sabchevski S.P., "Development of THz Gyrotrons at IAP RAS and FIR UF and Their Applications in Physical Research and High-Power THz Technologies," *IEEE Trans. on Terahertz Science and Technology*, vol. **5** (2015) 788-797.

[2] Idehara T., Tatematsu Y., Yamaguchi Y., Khutoryan E.M., Kuleshov A.N., Ueda K., Matsuki Y., Fujiwara T., "The Development of 460 GHz gyrotrons for 700 MHz DNP-NMR spectroscopy," *Journal of Infrared, Millimeter and Terahertz Waves*, **36** (2015) 613-627.

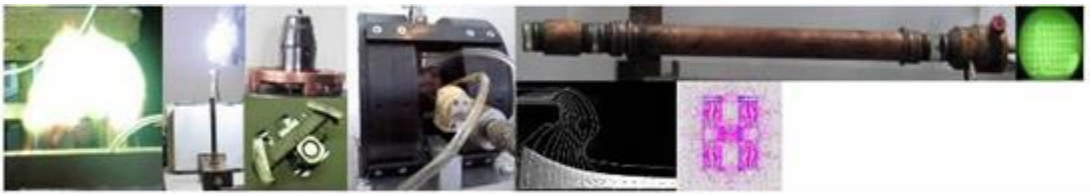
[3] Khutoryan E.M., Idehara T., Kuleshov A.N., Tatematsu Y., Yamaguchi Y., Matsuki Y., Fujiwara T., "Stabilization of Gyrotron Frequency by PID Feedback Control on the Acceleration Voltage," *Journal of Infrared, Millimeter and Terahertz Waves*, **36** (2015) 1157-1163.

[4] Idehara T., Khutoryan E.M., Tatematsu Y., Yamaguchi Y., Kuleshov A.N., Dumbrajs O., Matsuki Y., Fujiwara T., "High-Speed Frequency Modulation of a 460-GHz Gyrotron for Enhancement of 700-MHz DNP-NMR Spectroscopy," *Journal of Infrared, Millimeter and Terahertz Waves*, **36** (2015) 819-829.

[5] Tatematsu Y, Yusuke Y., Ichioka R., Kotera M., Saito T., Idehara T., "Development of the Multifrequency Gyrotron FU CW GV with Gaussian Beam Output," *Journal of Infrared, Millimeter, and Terahertz Waves*, **36** (2015) 697-708.

[6] Matsuki Y., IdeharaT., Fukazawa J., Fujiwara T., “Advanced instrumentation for DNP-enhanced MAS NMR for higher magnetic fields and lower temperatures,” *Journal of Magnetic Resonance*, **264** (2016) 107–115.

PRESENTING THE RESEARCH TEAMS OF THE CONSORTIUM



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Vacuum Electronic Department

Research & Development Team on MW and THz Tubes

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Research Areas:

- Development of MW & THz Clinotrons
- Development of Low-Voltage CRM
- Development of Microwave Plasma Ignition and Diagnostics Systems

Development of MW & THz Clinotrons

Our research group supervisor Prof. Boris P. Yefimov was one of the inventors of the clinotron, which is a compact powerful vacuum electron device of a BWO type in the millimeter and sub-millimeter ranges [1]. Currently, our research is focused on the development of compact medium power clinotron tubes in sub-THz and THz frequency ranges and on advancing their technology. Similar compact sources are widely used in the spectroscopy, non-destructive material testing, security, medicine, etc. A significant level of radiation output power in clinotrons is achieved by electron beam inclination to the surface of a slow-wave structure(SWS) as well as by the strong effect of electromagnetic waves reflection from the ends of SWS.

Consequently, all electrons approach closely the SWS and interact with a strong electric field that increases the output power. The beam-wave interaction process in the clinotron may be optimized applying a weak inhomogeneous magnetic focusing field. The main research results were presented recently in [2].

A sufficient increase of the output power in a THz clinotron has been demonstrated in the frequency range from 100 to 400 GHz. The tubes were operating in compact magnetic focusing systems with a preset distribution of the focusing field. Fig. 1 shows the developed 300 GHz and 400 GHz CW clinotrons and their focusing systems. These clinotrons have a frequency tuning range more than 20%, and output power of more than 100 and 40 mW, respectively.

The output power level of clinotrons depends strongly also on the ohmic losses. The losses are caused by the quality of the slow-wave structure manufacturing as wells as by the decrease of skin-layer depth, which is inversely proportional to the square root of the frequency. In order to decrease the influence of the ohmic losses and to increase the efficiency of the beam-wave interaction we proposed to utilize multistage slow-wave systems in the clinotron cavity [3].

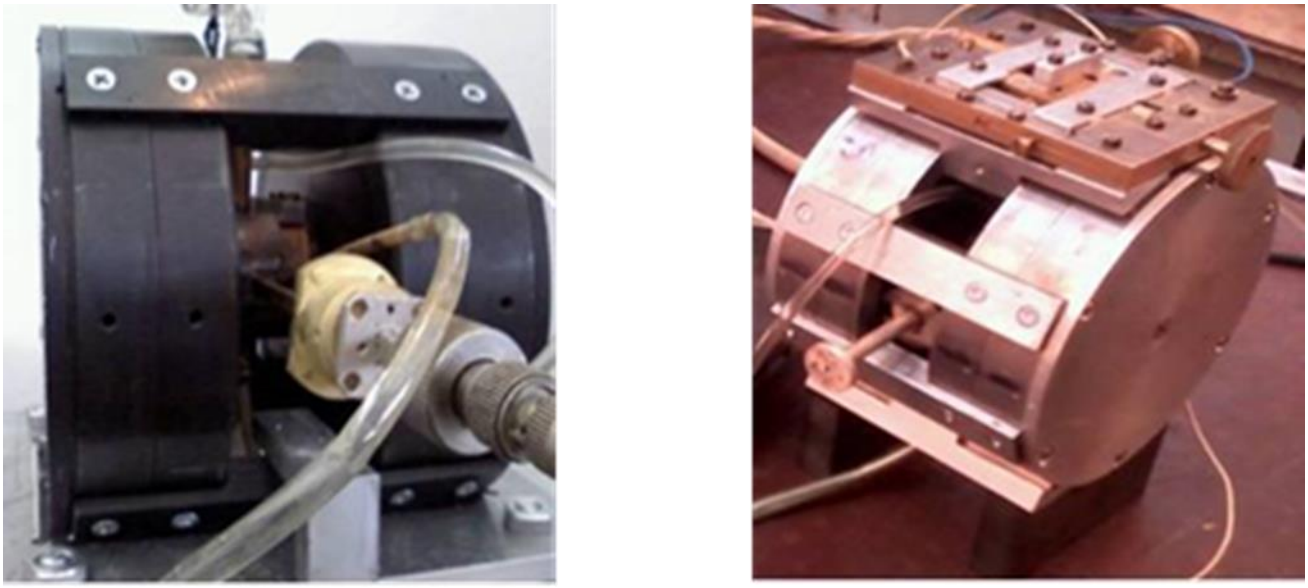

Fig.1 THz CW clinotron tubes packaged in compact 1 T focusing systems

In this connection, the physical features revealing the interaction of a non-relativistic sheet electron beam with the natural modes of the cavity resonator loaded by the SWS for O-type oscillators operating at millimeter and submillimeter ranges have been investigated [4]. The electromagnetic system with a three- and five-stage SWS in the waveguide with upper wall was proposed and studied. It was shown that hybrid surface-volume modes with high field amplitudes near the SWS as well as in the resonator space can be excited in the proposed systems. They are capable to provide a combined electronic-mechanical tuning that expands the frequency range. An excitation of natural modes of both the multistage and uniform grating in the cavity resonator with a 3-stage grating has been observed. Oscillations in a surface mode operation at 95.5 - 97.9 GHz with more than 2 W output power have been demonstrated in the experimental CW clinotron with a 3-stage grating [5].

Currently our group is involved in international collaborative projects on R&D of compact and powerful frequency tunable CW clinotrons for radar applications and spectroscopy in the frequency range from 40 to 420 GHz.

Development of Compact Low-Voltage CRM

The gyrotron, the most powerful Cyclotron Resonance Maser (CRM), is an extremely effective device used to generate high power microwave radiation in the sub-THz and THz ranges. It is used for microwave heating of thermonuclear plasma, radar and remote sensing technologies, many industrial applications, etc. At present, medium power CW gyrotrons are widely used as radiation sources in DNP-NMR spectroscopy, and THz imaging systems. Our current R&D projects include the development of compact and easy in use gyrotrons with sufficient levels of output power, high stability of both operating frequency and output power and frequency tuning in a wide range.

In our research we have developed several compact low-voltage gyrotrons [6, 7]. In order to explain the gyrotron low-voltage operation we proposed an additional mechanism of electron bunching by using inhomogeneous magnetic field in the cavity region. It was shown that the “negative mass instability” caused by relativistic dependence of the electron cyclotron frequency on the electron energy, is not the only mechanism (in the case of low accelerating voltages), which is responsible for the orbital bunching of the electrons initially uniformly distributed on a circle with a Larmor radius. The physical model of an additional electron bunching mechanism in the areas of weak magnetic mirrors has been proposed and the simulation results of the wave-particle interaction in accordance with the model are in a good agreement with the experimentally obtained results. Additionally, such bunching increases the efficiency of the gyrotron operation at low accelerating voltages [6].

The low-voltage CRM (Fig. 2) was developed and designed for operation at 8 GHz with an accelerating voltage of about 2.2 kV. The excitation of oscillations at the fundamental mode was obtained at a magnetic field of 0.28 T and an accelerating voltage of 2.2 kV. The starting current was found to be about 20 mA.

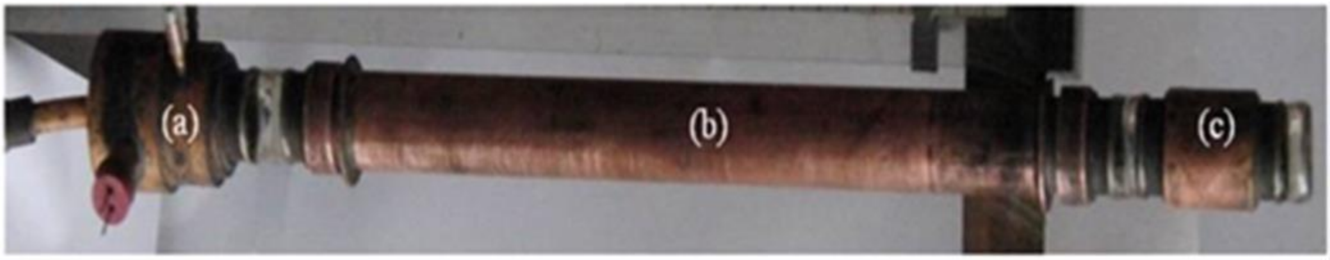

Fig 2. Design of the low-voltage CRM: magnetron-injection gun (a), resonant cavity (b), collector (c).

Another important parameter of the electromagnetic source is the frequency tuning in a wide frequency range. In the compact medium power gyrotrons the frequency tuning can be provided by both switching between cavity modes and changing the geometrical dimensions of the cavity. Application of a sheet helical electron beam instead of a helical electron beam in the resonator that consists of two cylindrical mirrors makes it possible to increase the electron efficiency of such gyrotron. We have made simulations of two gyrotrons with different geometries, namely with planar mirrors and with cylindrical mirrors in the frequency range of 75 GHz [8]. We have designed and tested also a planar magnetron injection gun (Fig. 3) forming a sheet helical electron beam at accelerating voltages ranging from 2 to 5 kV and pitch-factor around 2 [9].

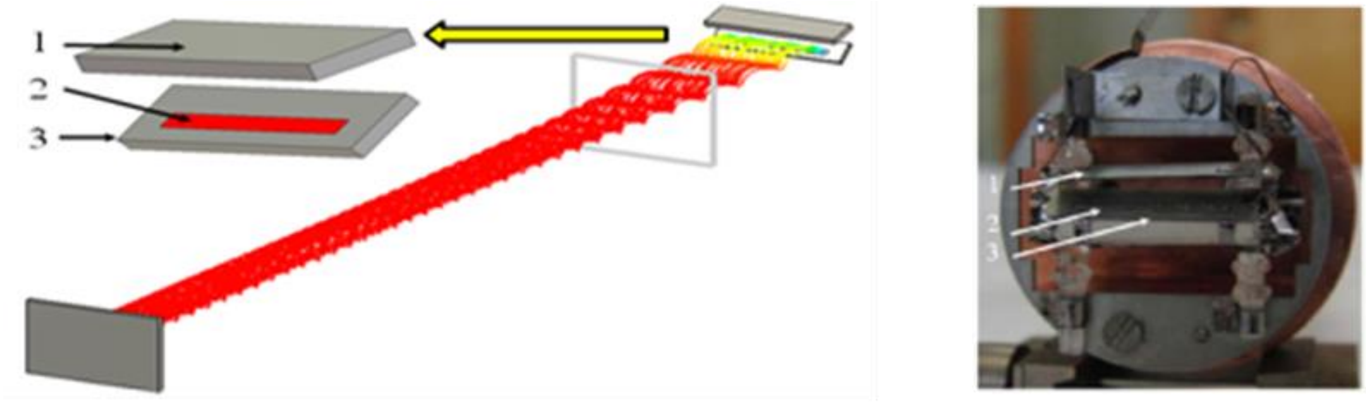

Fig. 3 Planar MIG design, sheet HEB configuration and a photo of the designed MIG

Development of High Voltage Power Supply with a High Stability

Stable operation of vacuum electron devices strongly depends on the parameters of the high-voltage (HV) power supply. For example, in the case of clinotrons the electron frequency tuning in a wide frequency range is determined by the dispersion properties of the used slow-wave structures. A voltage instability of the HV power supply of 5 mV results in a frequency instability close to 25 MHz at the operation frequency of 410 GHz and a beam voltage of 4,5 kV. At the same time, the spectral line width is not more than 1 MHz.

We have developed a compact HV power supply, which due to the application of the microcontroller scheme allows us to provide a remote control by a PC via USB using standard software packages such as National Instruments LabVIEW, Matlab, etc.

In the framework of our collaboration with Prof. Toshitaka Idehara and his colleagues from FIR Center at Fukui University and from the Institute for Protein Research of Osaka University the double proportional-integral-differential (PID) controller scheme for high stabilization of the gyrotron output power has been developed and tested [10]. The developed HV power supply for the clinotron allows us to use the same PID controller scheme.

In order to stabilize the clinotron output power the most simple way (in the case of stabilized voltage) is to provide a feedback in beam current circuit controlling the filament current. The stabilization of beam current (neglecting the effect of thermal shifts of the electromagnetic system at fixed frequency) results in a stabilization of the output power as well. It should be noted also that the inertia of the system is a serious limitation in the case of stabilization of the output power with fast changes. In such case it is necessary to use a double PID control, which can be realized in the clinotron with a three-electrode electron gun. The output power value measured with the help of both the waveguide coupler and the power meter is compared with the desired value and the PID controller provides the feedback to the filament power supply [10].

Development of Microwave Plasma Ignition and Diagnostics Systems

Experimental investigation of surface waves propagating along a single-conductor Goubau line and exciting torch MW discharge of erosion type is carried out. The prospect of Goubau line application as a transmitting line of electromagnetic energy in the THz range and also several possible practical applications of the line in new material processing technologies and semiconductor devices have been discussed in [11-12]. The description of MW setup features and additional elements for transmitted energy measurements in setup external circuit are also given in [11-12].

Investigations on the plasma instability states allow one to determine the main characteristics of the weakly ionized plasma existing in the magneto-hydrodynamic energy generators, plasma waveguides, gas lasers, and other devices. We study the applicability of the Doppler radar method to the diagnostic of the plasma parameters. At first stage, we have considered the method of remote measurement of the parameters of weakly ionized plasma arising in the noise generators, with the use of a homodyne two-frequency Doppler radar. This method is applied also to the analysis of more complex plasma formations [13].

In recent years, there is a great interest in a series of electric discharge effects that occur in different media. Specifically, in several papers a technique for creating a plasmoid (a counterpart of the globe-lightning) in a water-air medium by the action of an electrical discharge has been proposed and realized. Moreover, the mechanism of its existence has been described. Our research is focused on both the investigation of the low-energy discharge conditions in water that allows plasmoid excitation and on the specific features of the plasmoid glow [14-15].

References

[1] B.P. Yefimov, “BWT-Clinotron Based Stochastic Oscillators for Hidden Communications, Electronic Counter Action and Radio Masking in Millimeter-Wave Band,” *Telecom. and Radio Eng.*, vol. 67, no. 2 (2008) 161-175.

[2] S.S. Ponomarenko, S.A. Kishko, E.M. Khutoryan, A.N. Kuleshov, V.V. Zavertanniy, I.V. Lopatin, B.P. Yefimov, “400 GHz Continuous-Wave Clinotron Oscillator*,” IEEE Trans. Plasma Sci.*, vol. 41, no. 1 (2013) 82-86.

[3] S.S. Ponomarenko, S.A. Kishko, E.M. Khutoryan, A.N. Kuleshov, B.P. Yefimov, “On Ohmic Losses Decrease in THz BWO-Clinotron Oscillators,” Proc. Int. Conf. Infrared, Millimeter and Terahertz Waves (1-6 Sept 2013, Mainz on the Rhine) 33-34.

[4] A.N. Kuleshov, S.S. Ponomarenko, S.A. Kishko, V.V. Zavertanniy, E.M. Khutoryan, B.P. Yefimov, “Sub-THz CW Clinotron Oscillators with Increased Output Power,” Proc. IEEE Int. Vacuum Electronics Conference (22-24 Apr 2014, Monterey) 73-74.

[5] S.S. Ponomarenko, S.A. Kishko, E.M. Khutoryan, B.P. Yefimov, “Development of 94 GHz BWO - klynotron with 3-stage grating,” *Telecom. and Radio Eng.*, vol. 73, no. 3 (2014) 271- 281.

[6] S. Kishko, S. Ponomarenko, A. Kuleshov, V. Zavertanniy, B. Yefimov, I. Alexeff, “Low-Voltage Cyclotron Resonance Maser*,” IEEE Trans. on Plasma Science*, vol. 41, no. 9 (2013) 2475-2479.

[7] B.P. Yefimov, A. N. Kuleshov, V. F. Zhiglo, “Adiabatic Magnetron Injection Gun for Low-Voltage Gyrotron,” 8th Int. Vacuum Electronics Conf. IVEC 2007 (May 15-17, 2007, Kitakyushu, Japan) 1-2.

[8] S.A. Kishko, A.N. Kuleshov, M.Yu. Glyavin, I.V. Zotova, I.V. Zheleznov, N.S. Ginzburg, V.N. Manuilov, V.Yu. Zaslavskii, “Development of the 75-GHz planar gyrotron with transverse energy extraction,” *Journal of Communications Technology and Electronics*, vol. 59, no. 7 (2014) 777-781. (Russian original: *Radiotekhnika i Elektronika*, vol. 59, no. 7 (2014) 2014722-727).

[9] S.A. Kishko, S.S. Ponomarenko, A.N. Kuleshov, B.P. Yefimov, “Planar Magnetron-Injection Gun for Low-Voltage Quasi-Optical Gyrotron,” Proc. 15th International Vacuum Electronics Conference IVEC 2014 (22-24 April 2014, Monterey, California, USA) 439-440.

[10] Idehara T., Kuleshov A., Ueda K., “Power-Stabilization of High Frequency Gyrotrons Using a Double PID Feedback Control for Application to High Power THz Spectroscopy,” *J. Infrared, Millimeter and THz Waves*, vol. 35, no. 2, 159-168. DOI: 10.1007/s10762-013-0034-z.

[11] Puzanov A.O., Khorunzhiy M.O., Kuleshov A.N., Yefimov B.P., “Research Results and Applications of Torch Discharge in the Goubau Line,” *IEEE Transactions on Plasma Science*, vol. 39, no. 11 (2011) 2878-2879. DOI: 10.1109/TPS.2011.2166407.

[12] Yefimov B.P., Kuleshov A.N., Khorunzhii M.O., Mos'pan L.P., “The Properties of Microwave Discharge in the Goubau Line,” *High Temperature*, vol. 46, no. 6 (2008) 874-880.

[13] A.N. Kuleshov, M.O. Khorunzhiy, S.I. Khomenko, B.P. Yefimov, “Excitation of Long-Living Plasma in Open Air, and Doppler Radar Method for Investigation of Plasma Parameters,” 25th Symposium on Chemical Physics (6-8 Nov, 2009, Waterloo, Canada).

[14] Khorunzhiy M.O., Kuleshov A.N., Yefimov B.P., “Long-Living Plasma Excited by Electric Discharge in Water,” *IEEE Trans. Plasma Sci.* vol. 39, no. 11 (2011) 2648-2649.

[15] Khorunzhiy M.O., Yefimov B.P. and Kuleshov A.N., “Experimental Research on Discharge Processes in Water Solutions with Impurities,” *Telecom. and Radio Engi.*, vol. 65, no. 4 (2006) 335-343.

REGULAR PAPER

Use of a 187 GHz Extended Interaction Amplifier for Dynamic Nuclear Polarization Enhanced NMR

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Introduction

Nuclear Magnetic Resonance (NMR) is a widely used technique for obtaining information about materials. However because of the small magnetic moment of the nucleus NMR is not very sensitive and a significant amount of sample (typically > 10 mg) is required. The relatively large sample requirement makes various potential applications difficult for example the study of surfaces important for catalysts and biomolecules of limited availability. Electrons have a much larger magnetic moment (658 times that of ^{1}H, 2617 times that of ^{13}C) and Dynamic Nuclear Polarization (DNP) involves the transfer of the magnetisation of electron spins to nearby nuclei by irradiation at the appropriate frequency to induce electron-nuclear transitions thus producing a much larger NMR signal. For this transfer of magnetisation to take place a relatively high microwave power is needed and it is only since the development of CW gyrotrons with output powers of > 10 W at frequencies above 100 GHz that DNP has been developed for use on modern NMR spectrometers. Although these gyrotron sources work well, such that commercial DNP - NMR systems are now available using gyrotrons operating at frequencies of 263GHz, 395 GHz, or 527 GHz (for 400, 600 or 800 MHz ^{1}H NMR), they require an additional superconducting magnet which must be located at some distance from the NMR magnet so requiring significant extra space. In addition, since different radicals used as the source of electron polarization can have different resonant frequencies, either the gyrotron must be tuneable or the magnet field must be changed which, for convenience, requires a special NMR magnet. We have therefore investigated the use of a 187 GHz Extended Interaction Klystron (EIK) amplifier as a microwave source for DNP enhanced NMR.

Our set-up

The EIK amplifier is fed by a VDI Tx219 amplifier / x16 multiplier chain which has a maximum output of 71 mW. The multiplier chain can be driven either from an internal phase locked 11.700 GHz source, producing an output of 187.2 GHz, or from an external source. Figure 1 shows the arrangement. The output of the multiplier chain is fed via an attenuator and an isolator to the CPI VKY2444T2 EIK amplifier. This has a gain of 23.7 dB and produces more than 1W over a 0.7 GHz range centred on 187.09 GHz. The maximum power output is 9W with a 4dB (i.e. output > 3.5 W) bandwidth of 0.41 GHz. A quasi-optic transmission system is used to transmit the microwaves to the NMR probe. It is similar to one we described previously[1] and the first part of this system (Thomas Keating Ltd.) can be seen in Figure 2. The horn converts the output of the EIK to a Gaussian beam which is then transmitted via a flat and then a curved mirror to a polarising grid and on to a ferrite rotator. The ferrite rotates the incoming linear polarisation by 45° and the microwaves then pass through the second polarising grid. The two polarising grids and ferrite rotator combination forms a transmission mode isolator since any power reflected back from the NMR probe will have a polarisation at 45° relative to the outgoing beam which will be rotated by a further 45° such that its polarisation is 90° to the original beam and thus will not be transmitted through the next grid. This isolator, with an estimated insertion loss of ≤ 2 dB, protects the amplifier from damage due to any reflected power caused by poor coupling to the subsequent corrugated waveguide, the NMR probe or the sample. The microwaves are then transmitted down the NMR magnet bore through corrugated waveguide into the top of the NMR probe where they pass through a PTFE window in the cryostat and are focussed by two mirrors into the top of the rotor containing the sample[1]. Figure 3 shows a schematic of the microwave path through the probe. The beam waist (defined as 1/*e* amplitude) diameter at the top of the rotor is approximately 1.2 mm. Efficient polarisation transfer depends upon the electron spin relaxation time, T_1, (among other factors) which is longer at low temperatures. To achieve the maximum enhancement we use a modified Doty DI-4 Magic Angle Spinning NMR probe which is capable of spinning the sample stably at 8 kHz at 90 K for extended periods of time.

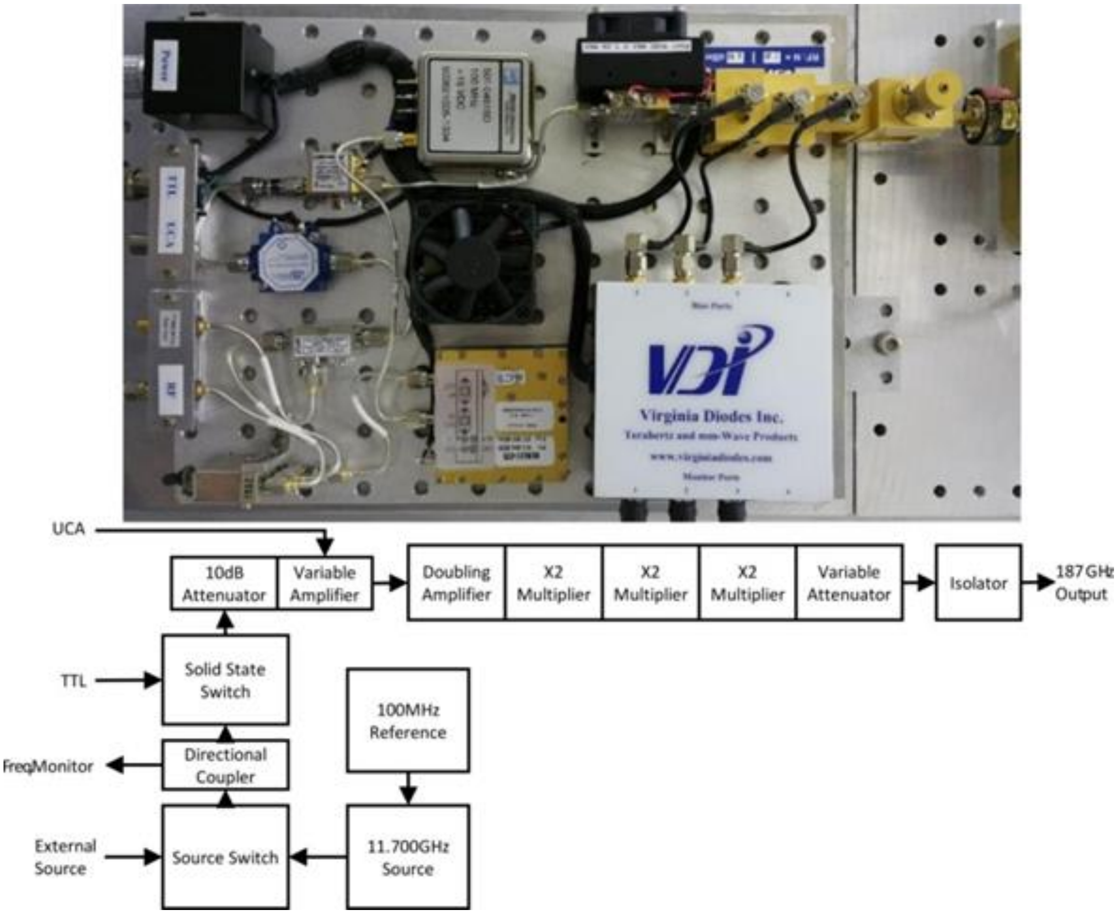

Figure 1 . Schematic diagram of the VDI 11.70 GHz -> 187.0 GHz amplifier – x16 multiplier chain with a photo above.

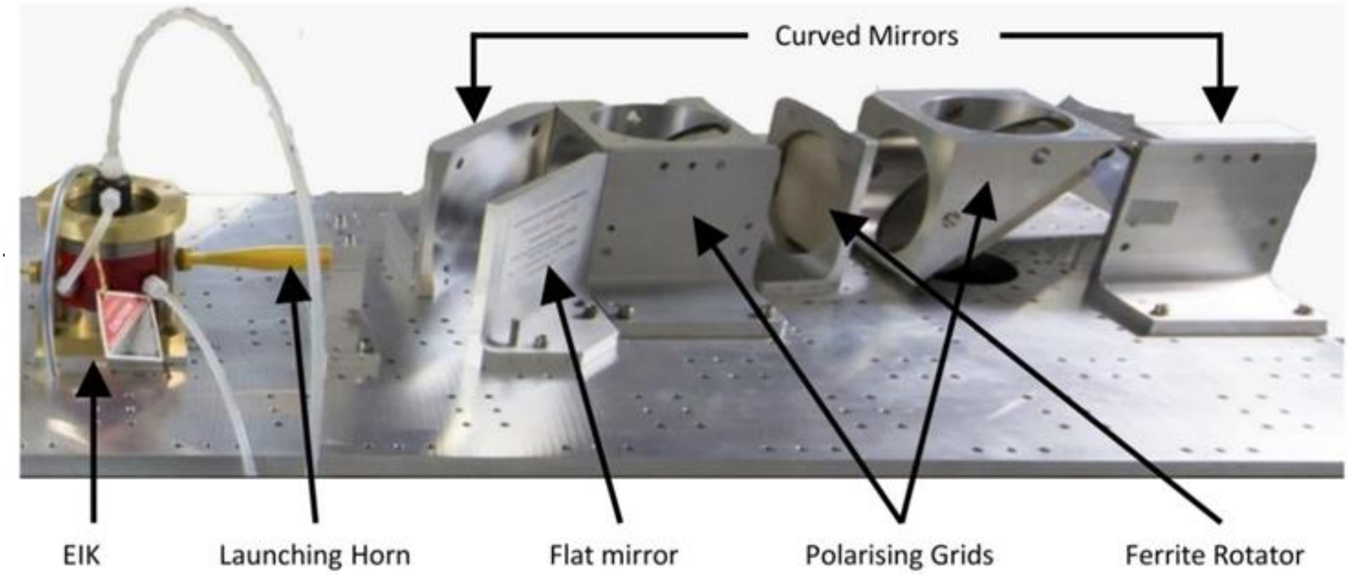

Figure 2. The first part of the quasi-optic transmission system showing the EIK amplifier on the left.

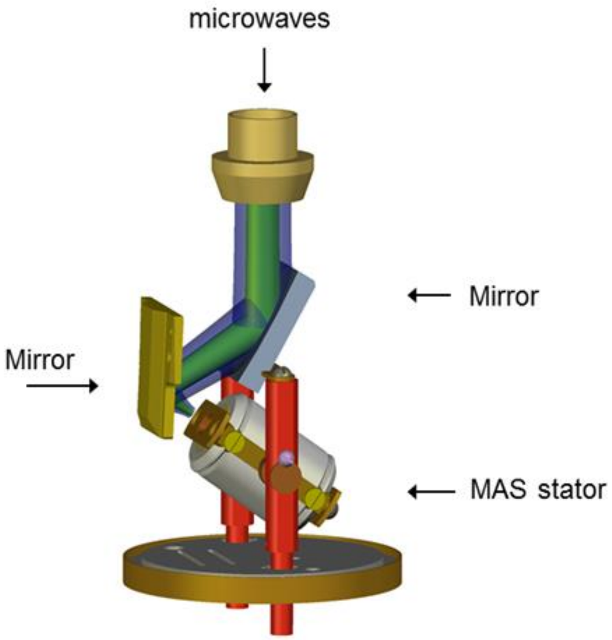

Figure 3. Schematic showing path of microwaves into the rotor of the Magic Angle Spinning NMR probe.

Performance

An example of the enhancements that can be achieved is shown in the inset to Figure 4 for a 1.5 mg sample of bacteriorhodopsin in purple membrane using glycerol-d_8, D_2O, H_2O mixture in a ratio 6:3:1 with 15mM AMUPOL as the radical solution[2]. The lower spectrum in the inset is the unenhanced signal x10 and the upper spectrum is the DNP enhanced signal with microwaves applied for 3 s before acquisition at 90 K. The enhancement is approximately 120. The enhancement as a function of the EIK output power is also shown in Figure 4 where it can be seen that ~ 3 W is sufficient for maximum enhancement corresponding to, at most, 1.5 W at the rotor top. In the commercial DNP-NMR systems the microwaves are coupled to the sample through the side of the rotor and also have to pass through the NMR coil. Considerably more power is needed to reach saturation indicating the improved efficiency of our quasi-optic system which uses a focussed microwave beam.

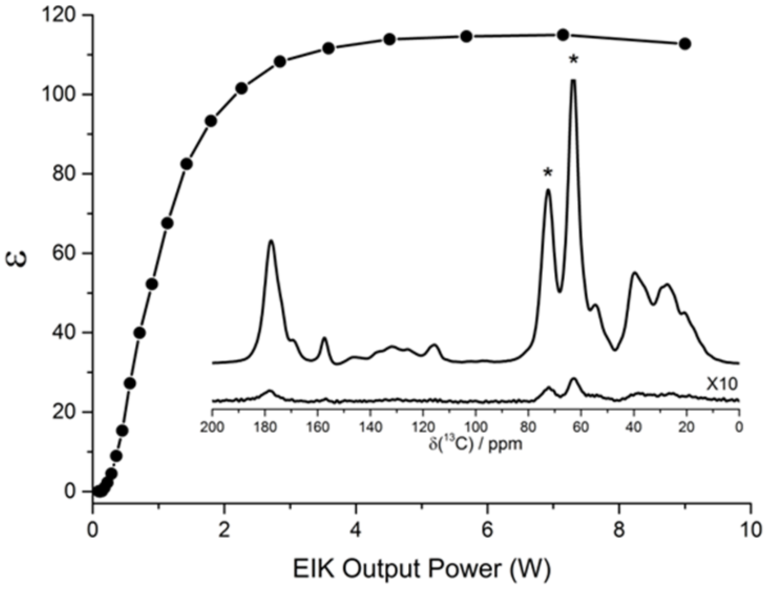

Figure 4 Enhancement of bacteriorhodopsin sample as a function of EIK output power. Inset is the 13C spectrum shown with and without microwaves

Typical enhancements for insoluble materials are much smaller than shown above, however they are often still very useful. An example is shown in Figure 5 for the zirconium-based metal-organic framework compound UiO-66-NH_2 which has a very high surface area and potential application for toxic gas removal. The upper (red) plot shows the ^{13}C spectrum with DNP enhancement after 9 minutes of acquisition. The lower (black) spectrum was acquired at room temperature for 21 hours. The signal-to-noise is about 3 times worse, thus the effective enhancement is ~35 corresponding to a saving in time for the same S/N of ~1000. Thus DNP allows previously impracticable data such as the ^{15}N spectrum to be obtained.

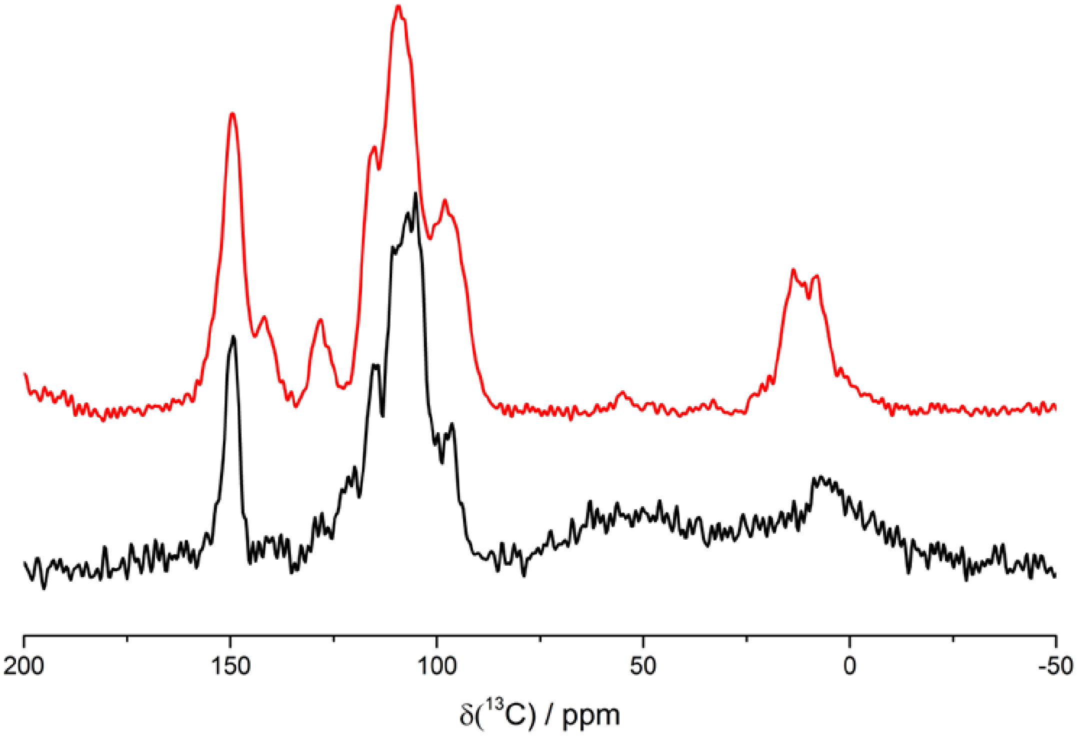

Fig.5 ^{13}C spectrum of UiO-66-NH_2, upper DNP enhanced at 90K, 9 minutes acquisition; lower 21 hours acquisition at room temperature.

Further examples of the performance of this system including for a pharmaceutical and for a surface functionalised material can be seen in our recent open access paper[2] listed below.

Acknowledgements

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References

1 *A spectrometer designed for 6.7 and 14.1T DNP-enhanced solid-state MAS NMR using quasi-optical microwave transmission*, K.J. Pike, T.F. Kemp, H. Takahashi, R. Day, A.P. Howes, E. V. Kryukov, et al., J. Magn. Reson. 215 (2012) 1–9. doi:10.1016/j.jmr.2011.12.006

2 *Dynamic Nuclear Polarization enhanced NMR at 187 GHz/284 MHz using an Extended Interaction Klystron amplifier,* Thomas F. Kemp, Hugh R.W. Dannatt, Nathan S. Barrow, Anthony Watts, Steven P. Brown, Mark E. Newton, Ray Dupree J. Magn. Reson. 265 (2016) 77–82, doi:10.1016/j.jmr.2016.01.021

LIST OF SELECTED RECENT PUBLICATIONS

Bibliography and links to selected recent publications on topics related to the research field of the International Consortium

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

Matsuki Y., IdeharaT., Fukazawa J., Fujiwara T., “Advanced instrumentation for DNP-enhanced MAS NMR for higher magnetic fields and lower temperatures,” *Journal of Magnetic Resonance*, 264 (2016) 107–115. DOI: 10.1016/j.jmr.2016.01.022.
http://www.sciencedirect.com/science/article/pii/S1090780716000781

Glyavin M.Yu., Goykhman M.B., Gromov A.V., Palitsin A.V., Panin A.N., Rodin Yu.V., Fil’chenkov S.E., "A waveguide high-pass filter system for measuring the spectrum of pulsed terahertz sources," *Infrared Physics & Technology* (2016). DOI: 10.1016/j.infrared.2015.12.031.
http://www.sciencedirect.com/science/article/pii/S1350449515301456

Kalynov Yu.K., Manuilov V.N., "A Wideband Electron-Optical System of a Subterahertz Large-Orbit Gyrotron," *IEEE Trans. on Electron Devices*, vol. 63 (2016) 491-496. DOI: 10.1109/TED.2015.2501023.
http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=7339435

Nusinovich G.S., Dumbrajs O., "Field Formation in the Interaction Space of Gyrotrons," *Journal of Infrared, Millimeter and Terahertz Waves*, vol. 37 (2016) 111–122. DOI: 10.1007/s10762-015-0192-2.
http://link.springer.com/article/10.1007%2Fs10762-015-0192-2

Dumbrajs O., Khutoryan E.M., Idehara T., "Hysteresis and Frequency Tunability of Gyrotrons," *Journal of Infrared, Millimeter and Terahertz Waves*, vol. 37 (2016). DOI: 10.1007/s10762-015-0240-y.
http://link.springer.com/article/10.1007%2Fs10762-015-0240-y

Zhang J., Illy S., Pagonakis I.Gr., Avramidis K.A., Thumm M., Jelonnek J., "Influence of emitter surface roughness on high power fusion gyrotron operation," *Nucl. Fusion*, vol. 56 (2016) 026002 (7pp). DOI: 10.1088/0029-5515/56/2/026002.
http://iopscience.iop.org/article/10.1088/0029-5515/56/2/026002

Ioannidis Z.C., Avramidis K.A., Tigelis I.G., "Selectivity Properties of Coaxial Gyrotron Cavities With Mode Converting Corrugations," *IEEE Trans. on Electron Devices* (2016) 8 pp.
DOI: 10.1109/TED.2016.2518217.
http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7393536&isnumber=4358746

Melnikova M.M., Rozhnev A.G., Ryskin N.M., Tyshkun A.V., Glyavin M.Y., Novozhilova, Y.V., "Frequency Stabilization of a 0.67-THz Gyrotron by Self-Injection Locking," *IEEE Trans. on Electron Devices* (2016). DOI: 10.1109/TED.2015.2512868.
http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=7381680&url=http%3A%2F%2Fieeexplore.ieee.org%2Fxpls%2Fabs_all.jsp%3Farnumber%3D7381680

Schaub S.C., Shapiro M.A., Temkin R.J., "Simple Expressions for the Design of Linear Tapers in Overmoded Corrugated Waveguides," *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 37 (2016) 100-110. DOI: 10.1007/s10762-015-0191-3.
http://link.springer.com/article/10.1007%2Fs10762-015-0191-3

Dumbrajs O., Saito T., Tatematsu Y., “Start-up scenario of a high-power pulsed gyrotron for 300 GHz band collective Thomson scattering diagnostics in the large helical device,” *Physics of Plasmas*, vol. 23 (2016) 023106. DOI: 10.1063/1.4941703.
http://scitation.aip.org/content/aip/journal/pop/23/2/10.1063/1.4941703

Bandurkin I.V., Kalynov Yu.K., Osharin, I.V., Savilov A.V., “Gyrotron with a sectioned cavity based on excitation of a far-from-cutoff operating mode,” *Physics of Plasmas*, 23 (2016) 013113.
DOI:10.1063/1.4940784.
http://scitation.aip.org/content/aip/journal/pop/23/1/10.1063/1.4940784.

Ginzburg N.S., Cross A.W., Golovanov A.A., Phelps, A.D.R., Romanchenko I.V., Rostov, V.V., Sharypov K.A., Shpak V.G., Shunailov S.A., Ul'masculov M.R., Yalandin M.I., Zotova I.V., "Coherent Summation of Emission From Relativistic Cherenkov Sources as a Way of Production of Extremely High-Intensity Microwave Pulses," *IEEE Trans. on Plasma Science*, (2016) pp.1-9. DOI: 10.1109/TPS.2016.2517670.
http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7395381&isnumber=4360151

Pagonakis I.Gr., Piosczyk B., Zhang J., Illy S., Rzesnicki T., Hogge J.-Ph., Avramidis K., Gantenbein G., Thumm M., Jelonnek J., “Electron trapping mechanisms in magnetron injection guns,” *Physics of Plasmas*, 23 (2016) 023105. DOI: 10.1063/1.4941705.
http://scitation.aip.org/content/aip/journal/pop/23/2/10.1063/1.4941705

Ishiyama S., Masamune K., Idehara T., “THz beam transmission demonstration experiment using metallic cladding polymer fibers,” *Transactions of the JSME* (in Japanese), vol. 82, no.833 (2016) 15-00449-15-00449). DOI: 10.1299/transjsme.15-00449.
https://www.jstage.jst.go.jp/article/transjsme/advpub/0/advpub_15-00449/_article

Thomas F. Kemp, Hugh R.W. Dannatt, Nathan S. Barrow, Anthony Watts, Steven P. Brown, Mark E. Newton, Ray Dupree, “Dynamic Nuclear Polarization Enhanced NMR at 187 GHz/284 MHz Using an Extended Interaction Klystron Amplifier,” *J. Magn. Reson*. 265 (2016) 77–82. (Open Access). DOI: 10.1016/j.jmr.2016.01.021.
http://www.sciencedirect.com/science/article/pii/S109078071600077X

B. Publications by other authors

Bandurkin I.V., Kalynov Yu.K., Osharin, I.V., Savilov A.V., “Gyrotron with a sectioned cavity based on excitation of a far-from-cutoff operating mode,” *Physics of Plasmas*, 23 (2016) 013113. DOI:10.1063/1.4940784.
http://scitation.aip.org/content/aip/journal/pop/23/1/10.1063/1.4940784.

Fu Wenjie, Guan Xiaotong, Yan Yang, “High harmonic terahertz confocal gyrotron with nonuniform electron beam,” *Physics of Plasmas*, 23 (2016) 013301. DOI: 10.1063/1.4939213.
http://scitation.aip.org/content/aip/journal/pop/23/1/10.1063/1.4939213

Liu W., LuY., He Z., Li W., Wang L., Jia Q., "Broad-tunable terahertz source with over-mode waveguide driven by train of electron bunches," *Opt. Express*, 24 (2016) 4109-4116. DOI:10.1364/OE.24.004109.
https://www.osapublishing.org/oe/abstract.cfm?uri=oe-24-4-4109

Zhou Y., Zhang Y., Liu S., "Electron-Beam-Driven Enhanced Terahertz Coherent Smith-Purcell Radiation Within a Cylindrical Quasi-Optical Cavity," IEEE Trans. on Terahertz Science and Technology, (2016) pp.1-6. DOI: 10.1109/TTHZ.2016.2516524.
http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7404045&isnumber=5741778

K.-E. Peiponen, Zeitler J.A., “Terahertz Spectroscopy Theory,” *Reference Module in Chemistry, Molecular Sciences and Chemical Engineering*, Elsevier, (2016).
DOI: 10.1016/B978-0-12-409547-2.12085-2.
(http://www.sciencedirect.com/science/article/pii/B9780124095472120852)

Venckevičius R, Kašalynas I., Valušis G., “ ‘Color’ photography at terahertz frequencies,” 22 Feb 2016, SPIE Newsroom.
DOI: 10.1117/2.1201601.006285.
http://spie.org/newsroom/technical-articles/6285-%E2%80%98color%E2%80%99-photography-at-terahertz-frequencies?highlight=x2406&ArticleID=x117011

Zheng-Di Li, Chao-Hai Du, Xiang-Bo Q, Li Luo, Pu-Kun Liu, “A 0.33-THz second-harmonic frequency-tunable gyrotron,” *Chin. Phys. B*, vol. 25, no. 2 (2016) 029401.
DOI: 10.1088/1674-1056/25/2/029401.
http://iopscience.iop.org/article/10.1088/1674-1056/25/2/029401/meta

Guo Liu, Ran Yan, Yong Luo, Shafei Wang, "A TE13 Mode Converter for High-Order Mode Gyrotron-Traveling-Wave Tubes," IEEE Trans. on Electron Devices, vol. 63, no.1 (2016) 486-490.
DOI: 0.1109/TED.2015.2499840.
http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7365557&isnumber=7365508

Mukesh Kumar Alaria, A.K. Sinha, H. Khatun, “Design and development of mode launcher for high frequency Gyrotron,” *Infrared Physics & Technology*, vol. 75 (2016) 187-192. DOI: 10.1016/j.infrared.2015.12.011.
http://www.sciencedirect.com/science/article/pii/S1350449515301948

Nusinovich G.S., “Remote Detection of Concealed Radioactive Materials by Using Focused Powerful Terahertz Radiation,” *Journal of Infrared, Millimeter, and Terahertz Waves*(2016) pp 1-21. DOI: 10.1007/s10762-016-0243-3.
http://link.springer.com/article/10.1007%2Fs10762-016-0243-3

Kim S.G., Sawant A., Lee I., Kim D., Choe M.S., Won J.-H., Kim J., So J., Jang W., Choi E., “System Development and Performance Testing of a W-Band Gyrotron,” *Journal of Infrared, Millimeter, and Terahertz Waves*, vol.37 , no. 3 (2016) 209-229. DOI: 10.1007/s10762-015-0221-1.
http://link.springer.com/article/10.1007%2Fs10762-015-0221-1

Bauer Y., Einat M., "Spaced Bitter Solenoid Design for a Continuous Wave 95-GHz Gyrotron," *IEEE Trans. Electron Devices*, (2016) 7 pp. DOI: 10.1109/TED.2016.2521743.
http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7401000&isnumber=4358746

Kumar N., Singh U., Bera A., Sinha A.K., “A review on the sub-THz/THz gyrotrons,” *Infrared Physics & Technology*, vol. 76 (2016) 38-51 DOI: 10.1016/j.infrared.2016.01.015.
http://www.sciencedirect.com/science/article/pii/S1350449515301316

Nusinovich G. S., Beaudoin B. L., Thompson C., Karakkad J. A., Antonsen T. M., “Limiting current of intense electron beams in a decelerating gap,” *Physics of Plasmas*, 23 (2016) 023114. DOI: 0.1063/1.4942175.
http://scitation.aip.org/content/aip/journal/pop/23/2/10.1063/1.4942175

Paoloni C., Mineo M., Yin H., Zhang L., He W., Robertson C., Ronald K., Phelps A., Cross A.,”A Microwave Coupler for W-Band Micro RE-Entrant Square Cavities,” *IET Microwaves, Antennas & Propagation*, (2016) 10 pp. DOI: 10.1049/iet-map.2015.0681.

http://digital-library.theiet.org/content/journals/10.1049/iet-map.2015.0681.

Barik R.K., Singh A.K., Shukla S., Singh T.P., Raju R.S., Park G.S., "Development of Nanoparticle-Based High Current Density Cathode for THz Devices Application," *IEEE Trans. on Electron Devices*, (2016) 7 pp. DOI:10.1109/TED.2016.2524539.
http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7415986&isnumber=4358746

Siaw T.A., Leavesley A., Lund A., Kaminker I., Han S, "A versatile and modular quasi optics-based 200 GHz dual dynamic nuclear polarization and electron paramagnetic resonance instrument," *Journal of Magnetic Resonance*, vol. 264 (2016) 131-153.
DOI: 10.1016/j.jmr.2015.12.012.
http://www.sciencedirect.com/science/article/pii/S1090780715003134

Cosentino A., "Terahertz and Cultural Heritage Science: Examination of Art and Archaeology," *Technologies*, vol. 4, no. 1, (2016) 6 pp. DOI: 10.3390/technologies4010006. (Open Access).
http://www.mdpi.com/2227-7080/4/1/6/htm

Kuznetsov S.A., Paulish A.G., Navarro-Cía M., Arzhannikov A.V., "Selective Pyroelectric Detection of Millimetre Waves Using Ultra-Thin Metasurface Absorbers," *Scientific Reports* 6 (2016) Article number: 21079. DOI: 10.1038/srep21079. (Open Access)
http://www.nature.com/articles/srep21079

Ioki K., Hiranai S., Moriyama S., Tanaka S., "Development of a dummy load and waveguide components for 1 MW CW gyrotron," (2016). DOI: 10.1016/j.fusengdes.2016.01.046.
http://www.sciencedirect.com/science/article/pii/S0920379616300461

NEW BOOKS

Christopher K. Walker, "**Terahertz Astronomy**," (CRC Press, 2016) 335 pp. Visit: Book review by Mircea Dragoman at:
http://www.osa-opn.org/home/book_reviews/2016/0116/terahertz_astronomy/

Fukunaga Kaori, "**THz Technology Applied to Cultural Heritage in Practice** 2016 (Cultural Heritage Science)," (Springer Verlag, 2016) 151 pp.
http://www.springer.com/us/book/9784431558835

Matthew N. O. Sadiku and Sudarshan R. Nelatury, "**Analytical Techniques in ectromagnetics**," (CRC Press, 2015) 246 pp.
https://www.crcpress.com/Analytical-Techniques-in-Electromagnetics/Sadiku-Nelatury/9781498709019

Andrew Seagar, "**Application of Geometric Algebra to Electromagnetic Scattering. The Clifford-Cauchy-Dirac Technique Hardcover**," (Springer Verlag, 2015) 179 pp.
http://www.springer.com/cn/book/9789811000881

Young Pak Lee, Joo Yull Rhee, Young Joon Yoo, Ki Won Kim, "**Metamaterials for Perfect Absorption**," (Springer Series in Materials Science, 2016) 176 pp.
http://www.springer.com/us/book/9789811001031

Neil A. Salmon (Ed.), Eddie L. Jacobs (Ed.) "**Millimetre Wave and Terahertz Sensors and Technology VIII**," (Proceedings of SPIE, 2015) 277 pp.

http://spie.org/Publications/Proceedings/Volume/9651

Hamlet K Avetissian, "**Relativistic Nonlinear Electrodynamics: The QED Vacuum and Matter in Super-Strong Radiation Fields**," (Springer Ser. on Atomic, Optical, and Plasma Physics, 2015) 506 pp.
http://www.springer.com/us/book/9783319263823

Matthias Maasch, "**Tunable Microwave Metamaterial Structures**," (Springer Theses, 2016) 138 pp.
http://www.springer.com/us/book/9783319281780

Ci-Ling Pan, "**Photonics for THz and Millimeter Waves in Ultra-Fast Wireless Communications**," (Wiley-IEEE Press, 2016) 320 pp.
http://eu.wiley.com/WileyCDA/WileyTitle/productCd-111839819X.html

AWARDS

From MIT News:

Professor R. Griffin receives the ACS E. Bright Wilson Award

Professor of chemistry and head of the Francis Bitter Magnet Laboratory honored for his outstanding contributions to the field of nuclear magnetic resonance (NMR) spectroscopy. He is well known and recognized pioneer and a leader in the development of a revolutionary new technique for signal enhancement through dynamic nuclear polarization (DNP) using gyrotron radiation. This method (DNP-NMR) enables researchers to see details in molecular structures (most notably proteins) that would require impossibly high fields and time in conventional NMR spectroscopy.

Robert Griffin will receive the E. Bright Wilson Award in Spectroscopy at the spring 2016 awards symposium of the American Chemical Society (ACS) Division of Physical Chemistry in San Diego on March 15th 2016.

For more information please visit:
http://news.mit.edu/2016/robert-griffin-receives-acs-e-bright-wilson-award-0219
http://phys-acs.org/awards/2016_national.html
http://chemistry.mit.edu/people/griffin-robert

NEWS FROM THE NET (OUR BROADER HORIZONTS)

New series of gyrotrons for fusion

"A contract between KIT and Thales was settled to develop and manufacture the series gyrotrons. The first step of this collaboration was the development of a prototype gyrotron for W7-X with an output power of 1 MW for CW operation at 140 GHz."
https://www.thalesgroup.com/en/worldwide/references/wendelstein-7x

The Quest for the Ultimate Vacuum Tube

"The cold-cathode traveling-wave tube, an ultracompact, ultraefficient source of RF waves, may finally be within reach," by Carter M. Armstrong.
http://spectrum.ieee.org/semiconductors/devices/the-quest-for-the-ultimate-vacuum-tube

From Microwaves to Motion to Light: Remarkable Progress toward a Quantum Transducer

"We showed that this device can convert microwave information into light just as well as it turns light back into microwaves. That was kind of a breakthrough for this effort. But we still have a very long way to go," by NIST.

For more detail see the original paper (open access): R.W. Andrews, A. P. Reed, K. Cicak, J. D. Teufel, K.W. Lehnert, "Quantum-enabled temporal and spectral mode conversion of microwave signals," *Nature Communications*, 6 (2015) Article number: 10021. DOI:10.1038/ncomms10021.
http://www.scientificcomputing.com/news/2016/02/microwaves-motion-light-remarkable-progress-toward-quantum-transducer

Medical Imaging Turns To Oft-Neglected Part Of Light Spectrum. "Advances in far-infrared spectroscopy could aid cancer diagnosis, but technology faces challenges," by Mitch Jacoby.
http://cen.acs.org/articles/93/i44/Medical-Imaging-Turns-Oft-Neglected.html

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Since our aim is to facilitate the exchange of information without overloading the contributors with routine technical procedures and details, there are not special requirements concerning the preparation of the submitted materials. Please use MS Word document in Times New Roman text format. The illustrative materials (e.g. photos, figures) are acceptable in any of the commonly used formats (JPG, GIF, TIFF, PNG). Each submission should begin with a title followed by the names and the affiliations of the authors. The manuscript could be structured as a research paper (divided in sections and subsections and including abstract, references, acknowledgements, etc.) or as a short note (letter) consisting of one or several paragraphs. There are no strict restrictions concerning the volume of the materials but it is expected that they will be between ½ -1 page for short notes and announcements and 5-8 pages for all other presentations.

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