High purity mode CW gyrotron covering the sub-THz to THz range using a 20 T super-conducting magnet

Toshitaka Idehara, Isamu Ogawa, Dietmar Wagner, *Member, IEEE*, Manfred Thumm, *Fellow, IEEE*, Kosuke Kosuga, and Svilen Petrov Sabchevski

***Abstract*— In this paper, we present the current status and both the ongoing investigation and the continuous improvements to the operational performance of a unique gyrotron, which is built using a 20 T superconducting magnet and holds a world record of 10 W THz wave generation at the highest frequency (1.08 THz) in continuous wave (CW) operation. Additionally, it has demonstrated high-purity single-mode generation on a sequence of modes that cover a wide range from sub-THz to THz frequencies at both fundamental and second-harmonic resonances of the electron cyclotron frequency. As an illustration, the measurements of the observed radiation patterns of eight output modes radiated from a currently used resonant cavity with a linear up-taper are presented and compared with the corresponding patterns simulated by scattering matrix calculations. A new design of an optimized cavity with a nonlinear up-taper, which improves further the mode purity of the generated output radiation has been proposed and is currently being implemented as a replacement of the existing resonator. The overall operational performance and the output characteristics of this gyrotron (called FU CW III in accordance with the nomenclature adopted at FIR UF Center) make it a versatile and appropriate source of coherent CW radiation for many novel applications in the fields of high-power THz science and technologies.**

***Index Terms*— Cavity resonators, Electron tubes, Gyrotrons, High power microwave generation, Submillimeter wave propagation, Submillimeter wave technology, Superconducting magnets, Terahertz radiation, Vacuum electronics.**

The work was supported partially by the Special Fund for Education and Research from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) in Japan, and SENTAN Project of the Japan Science and Technology Agency (JST).

T. Idehara (e-mail: idehara@fir.u-fukui.ac.jp), I. Ogawa (e-mail: ogawa@fir.u-fukui.ac.jp), and K. Kosuge are with the Research Center for Development of Far-Infrared Region at the University of Fukui (FIR UF), Fukui 910-8507 Japan .

D. Wagner is with Max-Planck Institute for Plasma Physics, Boltzmannstr. 2, D-85748 Garching, Germany (e-mail: dietmar.wagner@ipp.mpg.de).

M. Thumm is with Karlsruhe Institute of Technology (KIT), Institute for Pulsed Power and Microwave Technology (IHM), Kaiserstr. 12, 76131 Karlsruhe, Germany (e-mail: manfred.thumm@kit.edu).

S.P. Sabchevski was with the Research Center for Development of Far-Infrared Region at the University of Fukui (FIR UF), Fukui 910-8507 Japan. He is now with the Institute of Electronics of the Bulgarian Academy of Sciences, Sofia 1784, Bulgaria (e-mail: sabch@ie.bas.bg).

I. Introduction

In recent years, the advancement of the gyrotrons towards higher frequencies and output powers is accompanied by remarkable improvements in their operational performance (e.g. stable CW operation during long time intervals, continuous and step-wise frequency tunability in wide bands, possibility to modulate both the power and the frequency of the generated radiation, etc.). Nowadays, it is generally recognized and commonly accepted that the gyrotrons are the most-powerful sources of coherent radiation operating in CW regime in the region of the electromagnetic spectrum ranging from the sub-THz to the THz frequencies [1]–[3]. All these advantageous features of gyrotrons have opened an avenue to many novel and emerging applications in the high-power THz science and technologies [4]–[6].

Since the gyrotrons operate at resonances that correspond to the electron cyclotron frequency (which is linearly proportional to the intensity of the magnetic field in the resonant cavity– about 28 GHz per Tesla) or its harmonics, in order to exceed a frequency of 1 THz at a fundamental resonance one needs a field intensity as strong as around 36 T. Such high value is beyond the capabilities of the currently available and affordable superconducting magnets. During the previous decade, in order to overcome this severe limitation at FIR UF we used a high-current pulse magnet and/or operation at the second harmonic of the cyclotron frequency. Following such an approach we succeeded to demonstrate a breakthrough reaching a frequency of 1 THz. The output power at the second harmonic operation is about 10 W, and several kW at the fundamental [7], [8]. Another breakthrough crossing of the symbolic 1 THz threshold has been demonstrated by a gyrotron with a 40 T pulsed magnet developed at IAP in N. Novgorod, Russia. Their device produces coherent radiation with a frequency of 1.022THz and an output power of 1.5 kW (energy of 75 mJ in 50 μ sec pulses) [9].

Most of the applications, however, require long-pulse (at least several seconds) or CW radiation. Among them are such advanced spectroscopic methods as DNP-NMR (Nuclear Magnetic Resonance with a signal enhancement through Dynamic Nuclear Polarization) [10]–[16], ESR (Electron Spin Resonance) spectroscopy [17], [18], pump-and-probe technique based on XDMR (X-Ray Detected Magnetic Resonance)

[19], precise measurement of the HFS (hyperfine splitting) of the positronium [20]–[22], etc. The same requirement is imposed also by many other technologies that utilize gyrotrons as sources of powerful sub-THz and THz waves, for example, materials treatment (e.g. sintering of advanced ceramics, development of new functional materials) [23]–[25], biological and medical applications [26]–[28], just to name a few. Additional features demanded by some of the above-mentioned applications are frequency and amplitude modulation and stabilization, as well as frequency tunability. In order to satisfy all these essential requirements, a family of radiation sources operating in CW regime (called Gyrotron FU CW Series) has been developed using the experience gained from the previous series of pulsed tubes (Gyrotron FU).

In this paper, an additional feature of the high-performance gyrotrons, namely high mode purity of the output radiation and its realization in FU CW III by using a new cavity with a nonlinear up-taper is discussed. A high purity output mode operation is essential for a highly efficient conversion of the gyrotron cavity mode into a linearly polarized fundamental Gaussian mode in order to secure both a transmission of the wave beam with low losses and an efficient antenna coupling for various applications. Measured and calculated output mode patterns radiated from the existing cavity with a linear up-taper and the design of the newly optimized cavity with a nonlinear up-taper, which according to the numerical simulations improves significantly the mode purity are presented. The rest of the paper is organized as follows. In Section II, we outline the design of the gyrotron FU CW III with an existing cavity with a linear up-taper as well as the experimental setup used for its investigation. Both the measured and the corresponding calculated output mode patterns are discussed in Section III. In the fourth section, the design of a new cavity with a nonlinear up-taper optimized for the realization of broadband high-purity output mode operation is described. The conclusions and an outlook of the future work are presented in the final Section V.

II. Design of the gyrotron FU CW III and the experimental setup

Fig. 1 outlines the design of the Gyrotron FU CW III, which is built using a superconducting magnet with a maximum field intensity of 20 T. Its solenoid consists of two inner coils wound of NbTi wire and two outer coils made of Nb_3Sn. Both sections are fed by a common power supply and the field intensity of 20 T is generated at the coil current of around 290 A. The additional gun coils are three room-temperature copper solenoids.

The gyrotron tube consists of a triode magnetron injection gun (MIG), a resonant cavity, an output transmission waveguide, a collector and a sapphire output window. The tube is installed on the center axis of the room temperature bore (whose diameter is 52 mm) of the super-conducting magnet. The inside of the gyrotron tube is pumped out by a turbo-molecular pump down to 4×10^{-6} Pa. Two high voltage power supplies are connected to the cathode and the anode of the MIG. The potentials of the anode and the cathode with respect to the ground are varied from -5 kV to -13 kV and from -9 kV to -18 kV, respectively. The beam current can be varied from 80 mA to 500 mA by controlling the cathode filament current of the MIG.

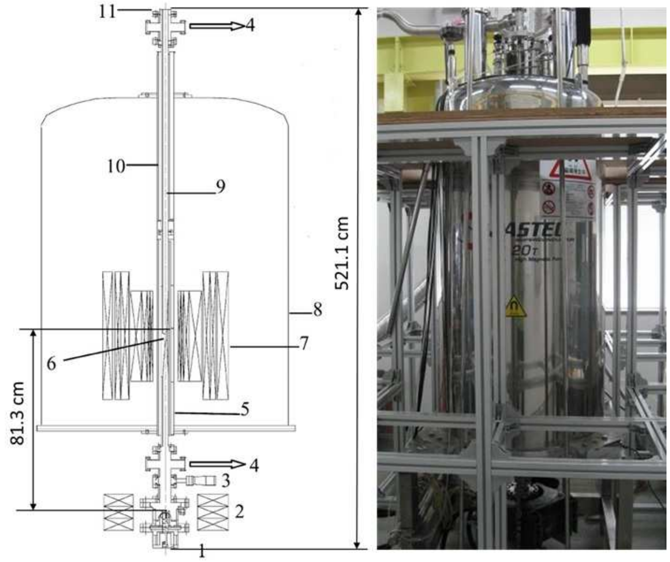

Fig. 1. Cross-sectional view (left) and a photo (right) of the gyrotron FU CW III: 1. Magnetron injection gun, 2. Additional gun coils, 3. Valve, 4. Connection to the vacuum system, 5. Jacket for the water cooling of the cavity, 6. Cavity resonator, 7. Coils of the superconducting magnet, 8. Cryostat, 9. Collector, 10. Jacket for water cooling of the collector, 11. Output window.

Fig. 2 shows the design of the existing resonant cavity. Its central part is a simple cylinder with two linear tapers at both ends. The diameter and the length of the cylindrical part are 3.9 mm and 10 mm, respectively. The cutoff taper ends up as a neck with 3 mm in diameter and then is connected to the beam tunnel. On the other side, the exit of the cavity opens as a linear up-taper with a length of 5 mm till ending up at a diameter of 8 mm. The next section of the linear up-taper (221 mm long) continues up to the circular waveguide with a diameter of 16 mm, which is connected to the output window made by a sapphire disk.

III. Radiation patterns from the existing cavity with a linear up-taper

As a measure of the mode purity of the output radiation, the radiation patterns for several operating cavity modes have been detected. They have been registered using a polymer sheet (located 165 mm away from the output window) and an infrared camera placed at a distance of 445 mm from the polymer sheet. Fig. 3 shows patterns of 8 different output modes with frequencies from 208.9 GHz to 478.6 GHz. In the case of an ideally cylindrical output waveguide system only intensity rings could be observed. The fact, however, that patterns with standing intensity distribution components have been measured indicates the presence of a departure from the axial symmetry due to, for example, a possible misalignment (e.g. tilt) of the output system or manufacturing errors of its parts. Since the location and direction of the possible tilt is not known, the corresponding patterns calculated using

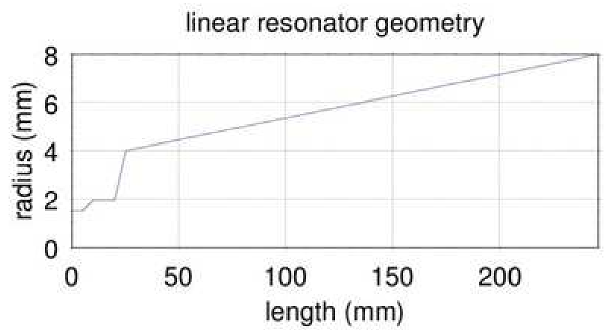

Fig. 2. Cross-section of the cylindrical gyrotron cavity with a two-section linear radius up-taper.

TABLE I

CALCULATED RESONANCE FREQUENCIES, MODE PURITIES, AND QUALITY FACTORS OF SEVERAL CAVITY MODES $TE_{m,p}$ RADIATED FROM THE EXISTING CAVITY WITH A LINER UP-TAPER.

Mode, (m,p)	Harmo-nic	Frequ-ency, (GHz)	Mode purity, (%)	Q_D	Q_Ω	Q_{tot}
1, 3	1	209.27	44.66	2173	3082	1863
1, 4	1	286.73	34.26	4736	15412	3623
1, 5	1	363.93	17.68	8486	17412	5705
1, 6	1	441.01	12.11	13770	19195	8018
0, 2	2	172.13	65.18	1412	12029	1264
0, 3	2	249.27	39.02	3466	14476	2797
0, 4	2	326.28	24.29	6787	16562	4814
0, 6	2	480.16	12.39	17384	20091	9320

a scattering-matrix code (which takes into account both the mode conversion in the up-taper and the reflections at its end) [29] have been rotated to approximately fit to the measured ones. Of course this has not been possible for the circular symmetric TE_{0n}-modes ($n = 2, 3, 4, 6$). The simulation results for the existing cavity with two-section linear up-taper are summarized in Table I. Near-field radiation patterns for several operation cavity modes/frequencies calculated using a scattering-matrix code [29] and corresponding to those in Fig. 3 are presented in Fig. 4.

It should be mentioned that the scattering matrix calculations (see Table I and Table II) provide an estimate of the purity of the operating modes with respect to the spurious modes that appear as a result of the mode conversion in the up-taper section of the cavity. Sometimes the experimentally measured standing wave patterns that result from the superposition of a co-rotating and a counter-rotating mode are used to evaluate the mode purity of the former with respect to the latter. In this case the mode purity, which is defined differently, namely as $\mu = P_r/(P_r + P_{cr})$ (P_r and P_{cr} being the powers of the rotating and counter-rotating modes, respectively) can be calculated by the relation, $\mu = 1/[1 + (1 - \sqrt{\rho})^2/(1 + \sqrt{\rho})^2]$, where ρ is the standing wave ratio $\rho = I_{max}/I_{min}$ [30]. The maximum and the minimum values of the intensity I_{max} and I_{min} are measured in an azimuthal direction along the outer ring of the standing pattern. This method, however, is applicable only to high resolution intensity data registered using for example an array of pyroelectric detectors as in [30], [31]. Due to the nonlinear response and the saturation of

TABLE II

CALCULATED RESONANCE FREQUENCIES, MODE PURITIES, AND QUALITY FACTORS OF SEVERAL CAVITY MODES $TE_{m,p}$ RADIATED FROM THE OPTIMIZED CAVITY WITH A NON-LINER UP-TAPER.

Mode, (m,p)	Harmo-nic	Frequ-ency, (GHz)	Mode purity, (%)	Q_D	Q_Ω	Q_{tot}
1, 6	1	440.98	99.44	9345	19195	6285
4, 5	1	469.86	99.91	10968	19011	6955
5, 5	1	503.60	99.93	13121	19361	7821
2, 7	1	554.88	99.94	16895	21430	9447
3, 8	2	668.35	99.90	28255	23417	12805
8, 7	2	762.42	99.85	41475	23647	15061
5, 9	2	816.99	99.65	51082	25619	17062
1, 11	2	825.81	99.64	51617	26325	17546
4, 10	2	859.03	99.88	59591	26524	18354
5, 10	2	894.67	99.68	66794	26912	19183
10, 9	2	987.89	99.64	93646	27050	20988
6, 11	2	1007.66	99.60	100134	28487	22178
4, 12	2	1013.65	99.40	104164	28919	22523
10, 10	2	1067.06	99.40	121872	28375	23016

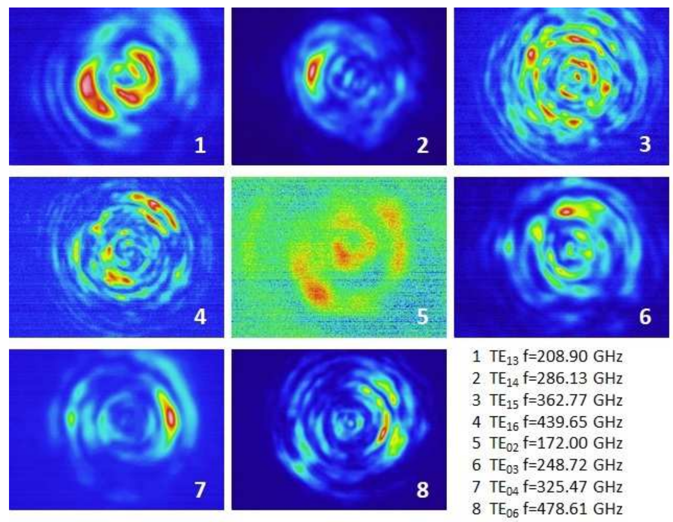

Fig. 3. Near-field radiation patterns of several operating cavity modes registered on a polymer sheet by an infrared camera. The distance between the output window and the polymer sheet is 165 mm, and between the latter and the IR camera 445 mm.

the intensity detected at the polymer sheet by an IR camera, the patterns presented in Fig. 3 are not suitable for such a treatment. A similar problem has been encountered in a previous study, where patterns burned on a sheet of paper have indicated distortions originating from the transformation of the symmetrical modes into non symmetrical modes of the output taper [32]. That is why in this study, we confined ourselves only to a qualitative analysis of the experimentally registered standing-wave patterns. Nonetheless, despite its limitations, this analysis shows convincingly that the currently used cavity with a linear up-taper needs a further optimization in order to achieve a higher mode purity operation.

IV. DESIGN OF A NEW CAVITY WITH A NONLINEAR UP-TAPER AND CALCULATED RADIATION PATTERNS FOR SEVERAL CAVITY MODES

The possibility of minimizing the transformation of the operating mode into spurious modes by optimizing the profile

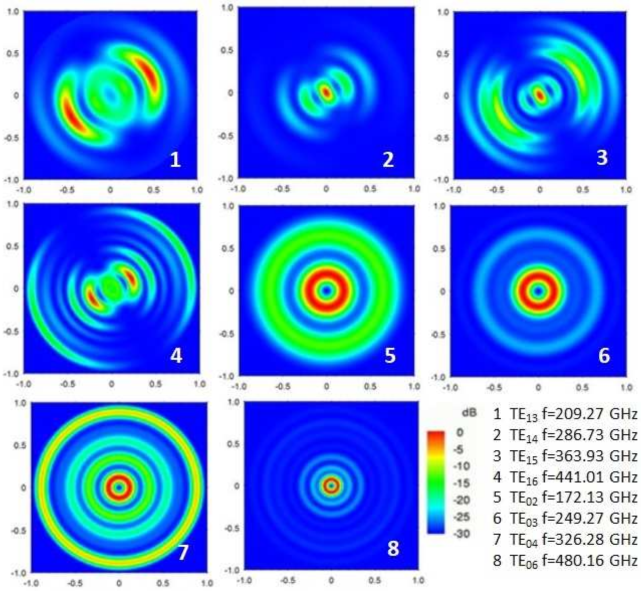

Fig. 4. Near-field radiation patterns for several operating cavity modes/frequencies calculated using a scattering-matrix code (corresponding to Fig. 3).

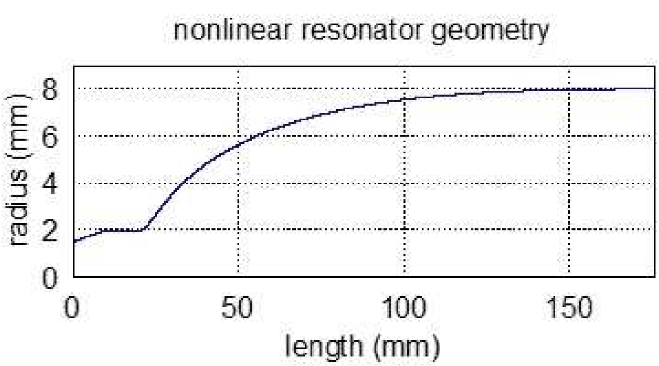

Fig. 5. Design sheet of a new cavity with a non-linear up-taper waveguide. Cavity radius 1.95 mm, cavity length (straight section) 10 mm, overall length (cavity and up-taper) 175.58 mm.

of the output waveguide has been demonstrated in a number of studies [33]–[35]. A powerful technique for such optimization involves an iterative process on each step of which the properties of the nonlinear taper are analyzed using dedicated scattering matrix codes [36]–[38].

The design sheet in Fig. 5 presents both the configuration and the dimensions of the new gyrotron cavity with a nonlinear up-taper, which is optimized for a high-purity operation. The simulation results for several second harmonic and fundamental modes excited at a rather high magnetic field are summarized in Table II. One can see that the calculated mode purity exceeds 99 % (i.e. one has almost absolute mode purity) for each of the considered cavity modes. This means that the new design of the cavity will improve significantly the operational performance of the present CW THz frequency-tunable gyrotron and thus make it an ideal radiation source for many applications in the area of high-power THz science and technologies.

V. Conclusions and an outlook

The Gyrotron FU CW III is a unique source of coherent radiation in a wide range spanning from sub-THz to THz frequencies. Moreover, it has demonstrated a 10 W CW operation at the highest frequency of 1.08 THz using a superconducting magnet with a maximum field intensity of 20 T. To the best of our knowledge, FU CW III is the only gyrotron in the world built on the basis of such a magnet. Additionally, many other modes have been excited at the fundamental and second harmonic resonances in CW and long-pulse operation. As a result, a step-tunability has been achieved in wide bands, namely from 164.3 GHz to 480.2 GHz at the fundamental resonances and from 356.7 GHz to 1.05 THz in the case of a second-harmonic operation, respectively. The output power has been measured calorimetrically (by the temperature increase of a water load) and ranges from 10 W at the highest frequency to several hundred watt at the fundamental operations and several tens watt at the second harmonic operations, respectively. Since the accuracy of such measurements during both CW and long pulse operation (several hundred milliseconds) is low, they have been repeated many times and therefore the average typical values are reported.

In order to evaluate the mode purity, the radiation patterns produced by eight cavity modes have been measured and analyzed. The experimental results indicate that a severe mode conversion takes place in the linear up-taper, which leads to the observed deterioration of the mode purity.

Aiming at an improvement of the mode purity an optimized resonant cavity with a non-linear up-taper has been designed and manufactured. The numerical experiments carried out using a scattering-matrix computer code have shown that in the new cavity the mode conversion is reduced drastically and mode purity better than 99 % may be achieved.

Since the gyrotron tube FU CW III is of demountable type, we plan to replace the existing resonator by the new cavity with a non-linear up-taper. The preparation for an experimental investigation of the presented computer-aided design of the optimized cavity is in progress now.

We believe that the expected improvement of the mode-purity together with the other already realized advantageous features of this gyrotron (for example, step-wise and continuous frequency tunability, high stability of the operation in long pulse and CW regimes, modulation of the frequency and the output power) will provide a remarkable operational performance that is demanded by many novel and prospective applications.

References

[1] M. Thumm, "State-of-the-Art of High Power Gyro-Devices and Free Electron Masers Update 2016," *KIT Scientific Reports*, vol. 7735, pp. 1–196, Jul. 2017, 10.5445/KSP/1000068193.

[2] R.A. Lewis, "A review of terahertz sources," *J. Phys. D: Appl. Phys.*, vol. 47, pp. 374001 (11pp) Aug. 2014, 10.1088/0022-3727/47/37/374001.

[3] J.H. Booske, R.J. Dobbs, C.D. Joye, C.L. Kory, G.R. Neil, G.–S. Park, J. Park, R.J. Temkin, "Vacuum Electronic High Power Terahertz Sources," *IEEE Trans. Terahertz Science and Technology*, vol. 1, no.1, pp. 54–75, Aug. 2011, 10.1109/TTHZ.2011.2151610.

[4] T. Idehara, S. Sabchevski, "Development and Applications of High–Frequency Gyrotrons in FIR FU Covering the subTHz to THz Range," *J. Infrared Millimeter and Terahertz Waves*, vol. 33, no. 7, pp. 667– 694, Jan. 2012, 10.1007/s10762-011-9862-x.

[5] M.Y. Glyavin, T. Idehara, S.P. Sabchevski, “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, pp. 788–797, Jun. 2015, 10.1109/TTHZ.2015.2442836.

[6] N. Kumar, U. Singh, A. Bera, Sinha A.K., “A review on the sub-THz/THz gyrotrons,” *Infrared Physics and Technology*, vol. 76, pp. 38–51, May 2016, 10.1016/j.infrared.2016.01.015.

[7] T. Idehara, S. Mitsudo, S. Sabchevski, M. Glyavin, I. Ogawa, “Gyrotron FU series– current status of development and applications,” *Vacuum*, vol. 62, no. 2–3, pp. 123–132, Jun. 2001, 10.1016/S0042-207X(00)00456-5.

[8] T. Idehara, H. Tsuchiya, O. Watanabe, La Agusu, S. Mitsudo, “The first experiment of a THz gyrotron with a pulse magnet,” *Int. J. Infrared and Millimeter Waves*, vol. 27, no. 3, pp. 319–331, Mar. 2006, 10.1007/s10762-006-9084-9.

[9] M.Y. Glyavin, A.G. Luchinin, 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, pp. 015101 (3 pp.), Jan. 2008, 101103/PhysRevLett.100.015101.

[10] V.S. Bajaj, C.T. Farrar, M.K. Hornstein, I. Mostovsky, J. Vieregg, J. Bryant, B. Elena, K.E. Kreischer, R.J. Temkin, R.G. Griffin,“ Dynamic nuclear polarization at 9 T using a novel 250 GHz gyrotron microwave source, ”*J. Magnetic Resonance* , vol. 160, pp. 85–90, Feb. 2003, 10.1016/j.jmr.2011.09.010.

[11] V. Denysenkov, M.J. Prandolini, M. Gafurov, D. Sezer, B. Endeward, T.F. Prisner, “Liquid state DNP using a 260 GHz high power gyrotron”, *Phys. Chem. Chem. Phys.* vol. 12, pp. 5786, Jun. 2010, 10.1039/c003697h.

[12] E.A. Nanni, A.B. Barnes, R.G. Griffin, and R.J. Temkin, “THz Dynamic Nuclear Polarization NMR”, *IEEE Trans. THz Sci. and Tech.*, vol. 1, pp. 145, Aug. 2011, 10.1109/TTHZ.2011.2159546.

[13] T. Idehara, Y. Tatematsu, Y. Yamaguchi, E.M. Khutoryan, A.N. Kuleshov, K. Ueda, Y. Matsuki, T. Fujiwara, “The Development of 460 GHz gyrotrons for 700 MHz DNP-NMR spectroscopy”, *J. Infrared, Millimeter and Terahertz Waves*, vol. 36 pp. 613–627, Mar. 2015, 10.1007/s10762-015-0150-z.

[14] M.K. Hornstein, V.S. Bajaj, R.G. Griffin, K.E. Kreischer, I. Mastovsky, M.A Shapiro, J.R. Sirigiri, R.J.Temkin, “Second harmonic operation at 460 GHz and broadband continuous frequency tuning of a gyrotron oscillator”, *IEEE Transactions on Electron Devices*, vol. 52, pp. 798–807, May 2005, 10.1109/TED.2005.845818.

[15] A.C. Torrezan, S.-T. Han, I. Mastovsky, M.A. Shapiro, J.R. Sirigiri, R.J. Temkin, A.B. Barnes, R.G. Griffin, “Continuous–Wave Operation of a Frequency-Tunable 460-GHz Second-Harmonic Gyrotron for Enhanced Nuclear Magnetic Resonance”, *IEEE Transactions on Plasma Science*, vol. 38, pp.1150–1159, Apr. 2010, 10.1109/TPS.2010.2046617.

[16] A.B. Barnes, E.A. Nanni, J. Herzfeld, R.G. Griffin, R.J. Temkin, “A 250 GHz gyrotron with a 3 GHz tuning bandwidth for dynamic nuclear polarization”, *Journal of Magnetic Resonance*, vol. 221, pp. 147–153, Aug. 2012, 10.1016/j.jmr.2012.03.014.

[17] S. Mitsudo, T. Higuchi, K. Kanazawa, T. Idehara, I. Ogawa, “High-field ESR measurements using Gyrotron FU series as radiation sources”, *J. Phys. Soc. Japan*, vol. 72 Suppl. B, pp. 172-176, 2003, 10.1143/JPSJS.72SB.172.

[18] S. Mitsudo, C. Umegaki, Y. Fujii and Y. Tatematsu, “Quasi-optical transmission system for a pulsed ESR system by using a gyrotron as a light source”, 40th Int. Conf. Infrared, Millimeter, and Terahertz waves (IRMMW-THz 2015, Hong Kong) pp. 1-2, Aug. 2015, 10.1109/IRMMW-THz.2015.7327943.

[19] A. Rogalev, J. Goulon, G. Goujon, F. Wilhelm, I. Ogawa, T. Idehara, “X-Ray Detected Magnetic Resonance at Sub-THz Frequencies Using a High Power Gyrotron Source”, *J. Infrared, Millimeter and Terahertz Waves*, vol. 33, pp. 777–793, Jul. 2012, 10.1007/s10762-011-9855-9.

[20] S. Asai, T. Yamazaki, A. Miyazaki, T. Suehara, T. Namba, T. Kobayashi, H. Saito, I. Idehara, I. Ogawa, S. Sabchevski, “Direct Measurement of Positronium Hyper Fine Structure: A New Horizon of Precision Spectroscopy Using Gyrotrons”, *J. of Infrared, Millimeter and Terahertz Waves*, vol. 3, no. 7, pp. 766-776, Jan. 2012, 10.1007/s10762-011-9864-8.

[21] T. Yamazaki, A. Miyazaki, T. Suehara, T. Namba, S. Asai, T. Kobayashi, H. Saito, I. Ogawa, T. Idehara, S. Sabchevski, “Direct observation of the hyperfine transition of ground-state positronium”, *Phys. Rev. Lett.*, vol. 108, pp. 253401 (5 pp.) Jun. 2012, 10.1103/PhysRevLett.108.253401.

[22] A. Miyazaki, T. Yamazaki, T. Suehara, T. Namba, S. Asai, T. Kobayashi, H. Saito, Y. Tatematsu, I. Ogawa, T. Idehara, “First millimeter-wave spectroscopy of ground-state positronium”, *Prog. Theor. Exp. Phys.*, pp. 011C01 (10 pp.) Jan. 2015, 10.1093/ptep/ptu181.

[23] H. Hoshizuki, S. Mitsudo, T. Saji, K. Matsuura, T. Idehara, M. Glyavin, A. Eremeev, T. Honda, T., Y. Iwai, H. Nishi, A. Kitano, J. Ishibashi, “High Temperature Thermal Insulation System for Millimeter Wave Sintering of B4C”, *Int. Journal of Infrared and Millimeter Waves*, vol. 26, no. 11, pp. 153–1541, Nov. 2005, 10.1007/s10762-005-0030-z.

[24] Mitsudo, H. Hoshizuki, T. Idehara, T Saito, “Development of material processing system by using a 300 GHz CW gyrotron”, *Journal of Physics: Conference Series*, vol. 51, no. 1, pp. 549–552, 2006, 10.1088/1742-6596/51/1/124.

[25] H. Aripin, S. Mitsudo, I. N. Sudiana, S.Tani, K. Sako, Y. Fujii, T. Saito, T. Idehara, S. Sabchevski, “Rapid Sintering of Silica Xerogel Ceramic Derived from Sago Waste Ash Using Sub-millimeter Wave Heating with a 300 GHz CW Gyrotron”, *Int. Journal of Infrared and Millimeter Waves*, vol. 26, no. 11, pp 1531–1541, May 2011, 10.1007/s10762-011-9797-2.

[26] T. Tatsukawa, A. Doi, M. Teranaka, H. Takashima, F. Goda, T. Idehara, I. Ogawa, S. Mitsudo, T. Kanemaki, “Development of Submillimeter Wave Catheter Transmitting a Gyrotron Output for Irradiation on Living Bodies”, *Int. J. Infrared and Millimeter Waves*, vol. 21, 1155–1167, Aug. 2000, 10.1023/A:1026435730192.

[27] N. Miyoshi, T. Idehara, E. Khutoryan, Y. Fukunaga, A.B. Bibin, S. Ito, S.P. Sabchevski, “Combined Hyperthermia and Photodynamic Therapy Using a Sub-THz Gyrotron as a Radiation Source”, *Journal of Infrared,Millimeter and Terahertz WavesVolume*, vol. 37, no. 8, pp. 805-814, Apr. 2016, 10.1007/s10762-016-0271-z.

[28] S.P. Sabchevski, T. Idehara, S. Ishiyama, N. Miyoshi, T. Tatsukawa, “A Dual-Beam Irradiation Facility for a Novel Hybrid Cancer Therapy”, *J. Infrared, Millimeter and Terahertz Waves*, vol. 34, no. 1, pp. 71–87, Jan. 2013, 10.1007/s10762-012-9945-3.

[29] D. Wagner, M. Thumm, G. Gantenbein, W. Kasparek, Idehara, “Analyzis of a complete gyrotron oscillator using the scattering matrix description”, *J. Infrared, Millimeter and Terahertz Waves*, vol. 19, no. 2, pp. 185–194, Feb. 1998. 10.1023/A:1022515506809.

[30] T. Idehara, I. Ogawa, S. Maeda, R. Pavlichenko, S. Mitsudo, D. Wagner, and M. Thumm,“Observation of mode patterns for high purity mode operation in the submillimeter wave Gyrotron FU VA,” *International Journal of Infrared and Millimeter Waves*, vol. 23, no. 9, pp. 1287–1295, Jul. 2002, 10.1023/A:1019666800167.

[31] I. Lee, A Sawant, M.S. Choe, D.-J. Lee, E. Choi, “Accurate identification of whispering gallery mode patterns of gyrotron with stabilized electro-optic imaging system,” Phys. Plasmas, vol. 25, pp. 013116-1, Jan. 2018. 10.1063/1.5017558.

[32] A.V. Gaponov, A.L. Gol’denberg, D.P. Grigor’ev, T.B. Pankratova, M.I. Petelin, V.A. Flyagin, “Experimental investigation of centimeter-band gyrotrons,” Radiophysics and Quantum Electronics, vol. 18, pp. 204-211, Oct. 1973. 10.1007/BF01036880.

[33] W.G. Lawson, ”Theoretical Evaluation of non-linear tapers for a high power Gyrotrons,” IEEE Transactions on Microwave theory and Techniques, vol.38, no.11, pp.1617-1622, Nov. 1990.

[34] O. Dumbrajs, M. Thumm, J. Pretterebner, D. Wagner ”A cavity with reduced mode conversion for gyrotrons”, Int. J. of Infrared and Millimeter Waves, vol. 13, no. 6, pp. 825-840, Jun 1992. 10.1007/BF01011598.

[35] D. Wagner, G. Gantenbein, W. Kasparek, M. Thumm, ”Improved gyrotron cavity with high quality factor”, Int. J. of Infrared and Millimeter Waves, vol. 16, no. 9, pp. 1481-1489, Sep. 1995. 10.1007/BF02274811.

[36] L. Ives, J. Neilson, W. Vogler, ”CASCADE - an advanced computational tool for waveguide components and window design,” Proceedings of the 2003 Particle Accelerator Conference, (Portland, Oregon U.S.A. May 12-16, 2003), Vol.1, pp. 269-271. 2003. 10.1109/PAC.2003.1288898.

[37] A.A. Bogdashov, Yu.V. Rodin, ”Mode Converter Synthesis by the Particle Swarm ptimization”, Int. J. of Infrared and Millimeter Waves, vol. 28, no. 8, pp. 627-638. Aug. 2007. 10.1007/s10762-007-9248-2.

[38] N. Chauhan, A. Mittal, D. Wagner, M.V. Kartikeyan, M.K. Thumm, ”Design and Optimization of Nonlinear Tapers using Particle Swarm Optimization”, Int. J. of Infrared and Millimeter Waves”, vol. 29, no. 8, pp. 792-798, Aug 2008. 10.1007/s10762-008-9366-5.

Toshitaka Idehara was born in Ibara Japan, on April 15, 1940. He received the B.S. degree in mathematics and the M.S. and D.S. degrees in physics from Kyoto University, Kyoto, Japan, in 1963, 1965, and 1968, respectively. After graduating from Kyoto University, he joined the University of Fukui, Fukui, Japan, and was a Lecturer from 1968 to 1970 and an Associate Professor from 1970 to 1990. During this term, he worked on fundamental plasma physics. After 1979, his interest was directed toward the development of high-frequency gyrotrons. From 1990 to 1999, he was a Professor in the Applied Physics Department, Fukui University, and from 1992 to 1999, he was the Head of the Laboratory for Application of Superconducting Magnet, Fukui University. Since 1999, he was a Professor and a founding Director of the Research Center for Development of Far-Infrared Region, University of Fukui (FIR UF). Since 2007 he was also a Supervisor of the research at FIR UF. From June 2004 to December 2010 he was an Editor in Chief of the International Journal of Infrared and Millimeter Waves and later Journal of Infrared, Millimeter, and Terahertz Waves. In 2009, he won the Prize for Science and Technology, The Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology of Japan, for Study on High Power THz Radiation Sources High Harmonic Gyrotrons. In 2011, he was awarded the Prize for Science and Technology from Fukui Prefectural Governer for Development of high power THz radiation sources Gyrotrons- and application to THz technologies. In 2016 he was awarded the Kenneth J. Button Prize for outstanding contributions to the development of high power THz radiation sources (harmonic gyrotrons) and their applications to high power THz spectroscopy. His current research interests include development of frequency tunable, sub-THz and THz gyrotrons and their applications to high-power THz technologies, novel spectroscopic techniques (NMR-DNP, ESR) and advanced technologies.

Isamu Ogawa was born in Hamada, Japan, on August 15, 1955. He received the B.S. and M.S. degrees in physics from Ehime University, Matsuyama, Japan, in 1979 and 1981, respectively, and the D.S. degree in physics from Nagoya University, Nagoya, Japan, in 1987. After graduating from Nagoya University, he joined Fukui University, Fukui, Japan. From 1989 to 1991, he was a Research Associate. Since 1991, he has been an Associate Professor in the Cryogenic Laboratory, Fukui University and then in the Research Center for Development of Far-Infrared Region (FIR UF Center). From 2004 till present he is a Professor at FIR UF. His research interests are in the fields of the quasi-optical systems and transmission lines, plasma scattering measurements, development, experimental study and application of gyrotrons, and developmen of novel technologies in the far-infrared region.

Dietmar Wagner was born in Schwäbisch Hall, Germany, in 1963. He received the Dipl.-Ing. and Dr.-Ing. degrees in electrical engineering from the University of Stuttgart in 1990 and 1996 respectively. He worked on high power millimeter wave transmission line components for his doctoral dissertation and his postdoctoral research at the Institute for Plasma Research at the University of Stuttgart, Germany. From 1999 until 2001 he was with the Gyrotron group at CPI Microwave Power Products Division in Palo Alto, California, where he worked on the design and development of high power Gyrotron oscillators. In 2001 he joined the ECRH group of the Max-Planck Institute for Plasma Physics in Garching, Germany, where he works on the application of high power millimeter waves for fusion plasma heating. Since 2011 he is a lecturer of High Power Microwave Technology at the Universit Aix-Marseille, France.

Manfred Thumm (SM94-F02) was born in Magdeburg, Germany, on August 5, 1943. He received the Dipl. Phys. and Dr. rer. nat. degrees in physics from University of Tbingen, Germany, in 1972 and 1976, respectively.

At the University of Tbingen he was involved in the investigation of spin-dependent nuclear forces in inelastic neutron scattering. From 1972 to 1975 he was Doctoral Fellow of the Studienstiftung des deutschen Volkes. In 1976 he joined the Institute for Plasma Research in the Electrical Engineering Department of the University of Stuttgart, Germany, where he worked on RF production and RF heating of toroidal pinch plasmas for thermonuclear fusion research. From 1982 to 1990 his research activities were mainly devoted to electromagnetic theory and experimental verification in the areas of component development transmission of very high power millimeter waves through oversized waveguides and of antenna structures for RF plasma heating with microwaves.

In June 1990 he became a Full Professor at the Institute of RF Engineering and Electronics of the University of Karlsruhe, Germany, and Head of the Gyrotron Development and Microwave Technology Division, Institute for Technical Physics, Research Center Karlsruhe (Forschungszentrum Karlsruhe: FZK). From April 1999 to September 2011, he was the Director of the Institute for Pulsed Power and Microwave Technology, FZK, where his current research projects have been the development of high power gyrotrons, dielectric vacuum windows, transmission lines and antennas for nuclear fusion plasma heating, and industrial material processing. In 2009, the University of Karlsruhe and the FZK have merged to the Karlsruhe Institute of Technology (KIT). M. Thumm has authored/co-authored 6 books, 21 book chapters, 383 research papers in refereed scientific journals, and more than 1480 conference proceedings articles. He holds 14 patents on active and passive microwave devices.

He was member of the IEEE EDS Vacuum Devices Technical Committee and the NPSS PSAC Executive Committee, and is member of the Chapter MN6 Committee Vacuum Electronics and Displays of the Information Technical Society in German VDE (Chairman from 1996 to 1999) and member of the German Physical Society. From 2007 to 2008 he was the vice chairman of the Founding Senate of the KIT. From 2008 to 2010 he was the deputy head of the Topic Fusion Technology of the KIT Energy. He was the General Chair of the IRMMW-THz 2004 and IEEE ICOPS 2008 Conference in Karlsruhe, Germany. He has been a member of the International Organization and Advisory Committees of many International Conferences and a member of the Editorial Boards of several ISI refereed journals. From 2003 to 2010 he was the ombudsman for upholding good scientific practice at FZK/KIT. Since 2012 he has been Editor for Vacuum Electron Devices of IEEE Trans. on Electron Devices, Distinguished Lecturer of IEEE NPSS, KIT Distinguished Senior Fellow and member of the International Advisory Committee of Cooperative Innovation Centre of THz Science in China. Since 2016 he serves as member of the Scientific Advisory Council of the Leibniz Institute for Plasma Science and Technology Greifswald.

He was awarded with the Kenneth John Button Medal and Prize 2000, in recognition of outstanding contributions to research on the physics of gyrotrons and their applications. In 2002, he was awarded the title of Honorary Doctor, presented by the St. Petersburg State Technical University, for his outstanding contributions to the development and applications of vacuum electron devices. He received the IEEE-EDS 2008 IVEC Award for Excellence in Vacuum Electronics for outstanding achievements in the development of gyrotron oscillators, microwave mode converters and transmission line components, and their applications in thermonuclear fusion plasma heating and materials processing. Together with two of his colleagues he received the 2006 Best Paper Award of the Journal of Microwave Power and Electromagnetic Energy and the 2009 CST University Publication Award. In 2010 he was awarded with the IEEE-NPSS Plasma Science and Applications Award for outstanding contributions to the development of high power microwave sources (in particular gyrotrons) for application in magnetically confined fusion plasma devices as well as for stimulation and establishing of extensive international co-operations. He is a winner of the 2010 open grant competition of the Government of the Russian Federation to support scientific research projects implemented under supervision of Leading Scientists at Russian institutions of higher education (with Novosibirsk State University). Together with A. Litvak and K. Sakamoto he has been the recipient of the EPS Plasma Physics Innovation Prize 2011 for outstanding contributions to the realization of high power gyrotrons for multi-megawatt long-pulse electron cyclotron heating and current drive in magnetic confinement nuclear fusion plasma devices. In 2012 he was awarded with the Heinrich Hertz Prize of the EnBW Foundation and the KIT for outstanding contributions to generation, transmission and mode conversion of high and very high microwave power for nuclear fusion and the HECTOR School Teaching Award in Embedded Systems Engineering. In 2017 he received the Exceptional Service Award of the IRMMW-THz Society and in 2018 the IEEE NPSS Merit Award.

Kosuke Kosuga was born in Shiga, Japan, on January 10, 1987. He received the B.S. and M.S. degrees in physics from University of Fukui, Fukui, Japan, in 2009 and 2011, respectively. He was involved in the studies and development of millimeter and submillimeter-wave gyrotrons for high-power THz science and technology in the FIR UF center from 2008 to 2011.

Svilen P. Sabchevski was born in Popovo, Bulgaria, on August 20, 1958. He received the M.Sc. degree in electronic engineering from Saint Petersburg State Electrotechnical University, Saint Petersburg, Russia, in 1984 (graduation with distinction summa cum laude), and the Ph.D. degree in physics from the Bulgarian Academy of Sciences, Sofia, Bulgaria, in 1991. After his graduation, he joined the Electron Beam Technologies Laboratory at the Institute of Electronics of the Bulgarian Academy of Sciences (IE-BAS), as a research fellow. He was an Associated Professor in this laboratory from 2001 to 2009. Since 2010 he is a Head of the Laboratory Plasma Physics and Engineering in IE-BAS. From 1999 to 2000, he was an Associate Professor and in the period 2002–2018 was appointed several terms as a Visiting Professor in the Research Center for Development of Far-Infrared Region, University of Fukui, Japan. His current research interests are in the fields of physics and applications of intense electron beams, computer-aided design of electron-optical systems, and vacuum electron devices. In recent years, he has been involved in several research projects on development and application of millimeter and submillimeter-wave gyrotrons for high-power THz science and technology.