# State-of-the-Art of High-Power Gyro-Devices - Update of Experimental Results 2023

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# Abstract

This report presents an update of the experimental achievements published in the review "State- of-the-Art of High-Power Gyro-Devices and Free Electron Masers", Journal of Infrared, Millimeter, and Terahertz Waves, **41**, No. 1, pp 1-140 (2020) related to the development of gyro-devices (Tables 2-34). Emphasis is on high-power gyrotron oscillators for long-pulse or continuous wave (CW) operation and pulsed gyrotrons for many other applications. In addition, this work gives a short update on the present development status of frequency step-tunable and multi-frequency gyrotrons, coaxial-cavity multi-megawatt gyrotrons, complex two-section stepped cavity gyrotrons, gyrotrons for technological and spectroscopy applications, relativistic gyrotrons, large orbit gyrotrons (LOGs), quasi-optical gyrotrons, fast- and slow-wave cyclotron autoresonance masers (CARMs), gyroklystron-, gyro-TWT- and gyrotwystron amplifiers, gyro-harmonic converters, gyro-BWOs and dielectric vacuum windows for such high-power mm-wave sources. Gyrotron oscillators (gyromonotrons) are mainly used as high power millimeter wave sources for electron cyclotron heating (ECH), electron cyclotron current drive (ECCD), stability control and diagnostics of magnetically confined plasmas for clean generation of energy by controlled thermonuclear fusion. The maximum pulse length of commercially available 140 GHz, megawatt gyrotrons employing synthetic diamond output windows is 30 minutes (CPI and European KIT-SPC-THALES collaboration). The world record parameters of the European tube are: 0.92 MW output power at 30 min. pulse duration, 97.5% Gaussian mode purity and 44% efficiency, employing a single-stage depressed collector (SDC) for electron energy recovery. PLL-frequency stabilization of such tubes has been demonstrated. A 1.5 MW version of this gyrotron is under development (IPP-KIT-THALES). The maximum output power of 1.5 MW in 4.0 s pulses at 45% efficiency was generated with the QST-CANON 110 GHz gyrotron. The first Japan 170 GHz ITER gyrotron prototype achieved 1 MW, 800 s at 55% efficiency and holds the energy world record of 2.88 GJ (0.8 MW, 60 min., 57 %). The Russian 170 GHz ITER gyrotron obtained 0.99 (1.2) MW with a pulse duration of 1000 (100) s and 57 (53) % efficiency. First frequency-injection-locked operation of a Russian 170 GHz-1 MW gyrotron has been demonstrated in short pulses using a PLL-frequency-stabilized 20 kW gyrotron master oscillator. The prototype tube of the KIT 2 MW, 170 GHz coaxial-cavity gyrotron (pulse duration 50 ms) achieved in 1 ms pulses the record power of 2.2 MW at 48% efficiency and 96% Gaussian mode purity. High-power CW gyrotron oscillators have also been successfully used in materials processing. Such technological applications require tubes with the following parameters: $f \geq 24$ GHz, $P_{out} = 4\text{-}50$ kW, CW, $\eta \geq 30\%$. Gyrotrons with pulsed magnet for various short-pulse applications deliver $P_{out} = 210$ kW with $\tau = 20\ \mu s$ at frequencies up to 670 GHz ($\eta \cong 20\%$), $P_{out} = 5.3$ kW at 1 THz ($\eta = 6.1\%$), and $P_{out} = 0.5$ kW at 1.3 THz ($\eta = 0.6\%$). The average powers produced by 94 GHz gyroklystrons, gyrotwystrons and gyro-TWTs are 10 kW, 5 kW and 2 kW, respectively.

# Keywords

Electron cyclotron maser, Gyrotron, Quasi-optical gyrotron, Gyroklystron-, Gyro-travelling-wave-, and Gyrotwystron amplifiers, Gyro-backward-wave oscillator, Cyclotron autoresonance maser, Dielectric vacuum windows

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# Zusammenfassung

Dieser Bericht bringt die im Review "State-of-the-Art of High-Power Gyro-Devices and Free Electron Masers", Journal of Infrared, Millimeter, and Terahertz Waves, **41**, No. 1, pp. 1-140 (2020) veröffentlichten experimentellen Ergebnisse zu Gyro-Röhren (Tabellen 2-34) auf den neuesten Stand. Der Schwerpunkt liegt dabei im Bereich der Entwicklung von Hochleistungs-Gyrotron-Oszillatoren für Langpuls- und Dauerstrichbetrieb (CW) sowie von gepulsten Gyrotrons für viele andere Anwendungen. Außerdem wird auch kurz über den neuesten Entwicklungsstand von stufenweise frequenzdurchstimmbaren Gyrotrons, Mehrfrequenz-Gyrotrons, Multi-MW-Gyrotrons mit koaxialem Resonator, Gyrotrons mit gestuftem, zweiteiligem Resonator, Gyrotrons für technologische und spektroskopische Anwendungen, relativistischen Gyrotrons, Large-Orbit-Gyrotrons (LOGs), quasi-optischen Gyrotrons, Zyklotron-Autoresonanz-Masern (CARMs) mit schneller oder langsamer Welle, Gyroklystron-, Gyro-TWT-, und Gyrotwystron-Verstärkern, Gyro-Harmonische-Konvertern, Gyro-Rückwärtswellen-Oszillatoren (BWOs) und von dielektrischen Vakuumfenstern für solche Hochleistungsmillimeterwellenquellen berichtet. Gyrotronoszillatoren (Gyromonotrons) werden vorwiegend als Hochleistungsmillimeterwellenquellen für Elektron-Zyklotron-Heizung (ECH), Elektron-Zyklotron-Stromtrieb (ECCD), Stabilitätskontrolle und Diagnostik von magnetisch eingeschlossenen Plasmen zur Erforschung der umweltfreundlichen Energiegewinnung durch kontrollierte Kernfusion eingesetzt. Die maximale Pulslänge von kommerziell erhältlichen 140 GHz, 1 Megawatt-Gyrotrons mit Austrittsfenstern aus künstlichem Diamant ist 30 min. (CPI und Europäische KIT-SPC-THALES Zusammenarbeitsgemeinschaft). Die Weltrekordparameter des europäischen 140 GHz-Megawatt-Gyrotrons sind: 0,92 MW Ausgangsleistung bei 30 min. Pulslänge, 97,5% Gaußsche Modenreinheit und 44% Wirkungsgrad mittels eines Kollektors mit einstufiger Gegenspannung (SDC) zur Energierückgewinnung. PLL-Frequenzstabilisierung solcher Röhren wurde gezeigt. Eine 1,5 MW Version dieses Gyrotrons ist in Entwicklung (IPP-KIT-THALES). Die maximale Ausgangsleistung von 1,5 MW bei 4,0 s Pulslänge und 45% Wirkungsgrad wurden mit dem QST-CANON 110 GHz Gyrotron erzeugt. Das erste japanische 170 GHz ITER-Prototyp-Gyrotron erreichte 1 MW, 800 s bei 55% Wirkungsgrad und hält den Energieweltrekord mit 2,88 GJ (0,8 MW, 60 min., 57 %). Das russische 170 GHz ITER-Gyrotron lieferte 0,99 (1,2) MW bei 1000 (100) s Pulslänge und 57 (53) % Wirkungsgrad. Erste Kurzpulsexperimente zum Frequenz-Injection-Locking eines russischen 170 GHz-1 MW Gyrotrons wurden mit Hilfe eines PLL-frequenzstabilisierten 20 kW Gyrotron-Master-Oszillators durchgeführt. Das KIT 2 MW, 170 GHz Prototyp-Gyrotron mit koaxialem Resonator (50 ms Pulslänge) erzielte 5 ms Pulsen die Rekordleistung von 2,2 MW bei 48% Wirkungsgrad und 96% Gaußscher Modenreinheit. CW-Gyrotrons finden jedoch auch in der Materialprozeßtechnik erfolgreich Verwendung. Dabei werden Röhren mit folgenden Parametern eingesetzt: $f \geq 24$ GHz, $P_{out}$ =4-50 kW, CW, $\eta \geq 30\%$. Gyrotrons mit gepulstem Magnet fürverschiedene Kurzpuls-Anwendungen arbeiten bei Frequenzen bis zu 670 GHz bei $P_{out} = 210$ kW und $\tau = 20$ µs ($\eta \cong 4\%$), $P_{out} = 5{,}3$ kW bei 1 THz ($\eta = 6{,}1\%$) und $P_{out} = 0{,}5$ kW bei 1,3 THz ($\eta = 0{,}6\%$). Die höchsten von 94 GHz Gyroklystrons, Gyrotwystrons und Gyro-TWTs erzeugten mittleren Leistungen sind 10 kW, 5 kW und 2 kW.

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# 1 Introduction

The possible applications of gyrotron oscillators (gyromonotrons, or just gyrotrons) and other electron cyclotron maser (ECM) fast-wave devices (see Table 1) span a wide range of technologies [1-8]. The plasma physics community has taken advantage of advances in producing high power micro- and millimeter (mm) waves in the areas of radio frequency (RF) plasma applications for magnetic confinement fusion studies, such as lower hybrid current drive (LHCD: 8 GHz), electron cyclotron heating and non-inductive electron cyclotron current drive (ECH&CD: 14-170 GHz), plasma production for numerous different processes and plasma diagnostic measurements, such as Collective Thomson Scattering (CTS) or heat-pulse propagation experiments. Other applications which await further development of novel high power mm-wave sources include deep-space and specialized satellite communication, high-resolution Doppler radar, radar ranging and imaging in atmospheric and planetary science, remote detection of concealed radioactive materials, ECR sources of highly ionized ions, submillimeter-wave and THz spectroscopy, materials processing and plasma chemistry.

Most works on ECM devices have investigated the conventional gyrotron [9-31] in which the wavevector of the radiation in an open-ended, irregular cylindrical waveguide cavity is almost transverse to the direction of the applied magnetic field, generating transverse electric (TE) electromagnetic (EM) waves near the electron cyclotron frequency or at one of its harmonics. Long-pulse and continuous wave (CW) gyrotrons delivering output powers of 0.1-1.2 MW at frequencies between 28 and 170 GHz have been used very successfully in thermonuclear fusion research for plasma ionization and start-up, ECH and local, current density profile control by non-inductive ECCD at system power levels up to 10 MW.

ECH has become a well-established heating method for both tokamaks [32-64] and stellarators [64-92]. The confining magnetic fields in present day fusion devices are in the range of $B_o$=1-3.6 Tesla. As fusion machines become larger and operate at higher magnetic field ($B_o \cong 5.5$T) and higher plasma densities in steady state, it is necessary to develop CW gyrotrons that operate at both higher frequencies and higher mm-wave output powers. The requirements of the new stellarator (W7-X) at the Max-Planck-Institute for Plasmaphysics in Greifswald, Germany, and the future tokamak experiment ITER (International Thermonuclear Experimental Reactor) in Cadarache, France, are between 18 and 40 MW at frequencies between 140 GHz and 170 GHz [23,26-31,39,57-61,65-86,92-116]. This suggests that mm-wave gyrotrons that generate output power of at least 1 MW, CW, per tube are required. Since efficient ECH needs axisymmetric, narrow, pencil-like mm-wave beams with well-defined polarization (linear or elliptical), single-mode gyrotron emission is necessary in order to generate a fundamental Gaussian beam mode ($TEM_{00}$). Single-mode 77-170 GHz gyromonotrons with conventional, cylindrical cavity, capable of 1.5 MW per tube, CW [23-31], and 2 MW coaxial-cavity gyrotrons [97-112] are currently under development. There has been continuous progress towards higher frequency and power but the main issues are still the long-pulse or CW cavity and collector operation. The availability of sources with fast frequency tunability would permit the use of a simple, non-steerable mirror antenna at the plasma torus for local current drive experiments [26-31,39,98-121]. Frequency tuning has been shown to be possible in quasi-optical Fabry-Perot cavity gyrotrons [122,123] as well as in cylindrical and coaxial cavity gyrotrons by frequency tuning in steps (different operating cavity modes) [124-159].

This report updates the present status and future prospects of gyrotrons and RF vacuum windows for ECH&CD in fusion plasmas and for ECR plasma sources for generation of multi-charged ions, soft X-rays and UV radiation [160-187] (Tables 2-13), the development of very high frequency gyrotrons for active plasma diagnostics [188-244], high-frequency sub-millimeter wave spectroscopy in various fields (e.g. Dynamic Nuclear Polarization (DNP) Nuclear Magnetic Resonance (NMR) spectroscopy, molecular spectroscopy, hyperfine structure of the positronium) [245-362], remote detection of concealed radioactive materials [363-366], wireless communication [367] and medical applications [368-373] (Tables 14-18) and of quasi-optical gyrotrons (Table 22). Gyrotrons also are successfully utilized in materials processing (e.g. advanced ceramic and metal-powder-compound sintering, nano-particle production, surface hardening or dielectric coating of metals and alloys, semiconductor production, penetrating rocks) as well as in plasma chemistry [1-8,374-403]. The use of gyrotrons for such technological applications appears to be of interest if one can realize a relatively simple, low cost device, which is easy in service (such as a magnetron). Gyrotrons with low magnetic field (operated at the 2nd harmonic of the electron cyclotron frequency), low anode voltage, high efficiency and long lifetime are under development. Mitsubishi in Japan [404] and Gycom in Russia [382,393-396,405-410] are also employing permanent magnet systems. The state-of-the-art in this area of gyrotrons for technological applications is summarized in Table 19.

The next generation of high-energy physics accelerators and the next frontier in understanding of elementary particles is based on supercolliders. For normal-conducting linear electron-positron colliders that would reach center-of-mass energies of > 1 TeV sources at 17 to 35 GHz with $P_{out}$ = 300 MW, $\tau$ = 0.2 μs and characteristics that allow approximately 1000 pulses per second would be necessary as drivers [411-414]. These must be phase-coherent devices, which can be either amplifiers or phase-locked oscillators. Such generators are also required for super-range high-resolution radar and atmospheric sensing [415-428]. Therefore, this report also gives an overview of the present development status of relativistic gyrotrons (Tables 20 and 21), fast- and slow-wave cyclotron autoresonance masers (CARM) (Tables 23 and 24), gyro-klystrons (Tables 25-27), gyrotron travelling wave tube amplifiers (Gyro-TWT) (Tables 28 and 29), gyrotwystron amplifiers (Tables 30-32), and broadband gyrotron backward wave oscillators (Gyro-BWO) (Tables 33 and 34).

The present report updates the experimental achievements (Tables 2 - 34) of gyro-devices reviewed in M. Thumm, State-of-the-Art of High-Power Gyro-Devices and Free Electron Masers, Journal of Infrared, Millimeter, and Terahertz Waves, 41, No. 1, pp. 1-140 (2020), and in KIT Scientific Report 7761 (2021). Former reviews were KfK Report 5235 (Oct 1993), FZKA Reports 5564 (Apr 1995),5728 (Mar 1996), 5877 (Feb 1997), 6060 (Feb 1998), 6224 (Jan 1999), 6418 (Feb 2000), 6588 (Mar 2001), 6708 (Feb 2002), 6815 (Feb 2003), 6957 (Feb 2004), 7097 (Feb 2005), 7198 (Feb 2006), 7289 (Feb 2007), 7392 (2008), 7467 (2009), and KIT Scientific Reports 7540 (2010), 7575 (2011), 7606 (2012), 7641 (2013), 7662 (2014), 7693 (2015), 7717 (2016), 7735 (2017) and 7750 (2018).

The list of references includes additional information about: principle and history of gyrotrons [437-452], effective cavity length [453], internal quasi-optical mode converters as transverse Gaussian beam or $HE_{11}$ mode output couplers [454-469], electron beam space-charge neutralization [470,471], CARMs, other gyro-amplifiers and gyro-BWOs [472-486], magnicons [487-489], gyro-harmonic converters [490-492], and free electron masers (FEMs) [429-436,493-522].

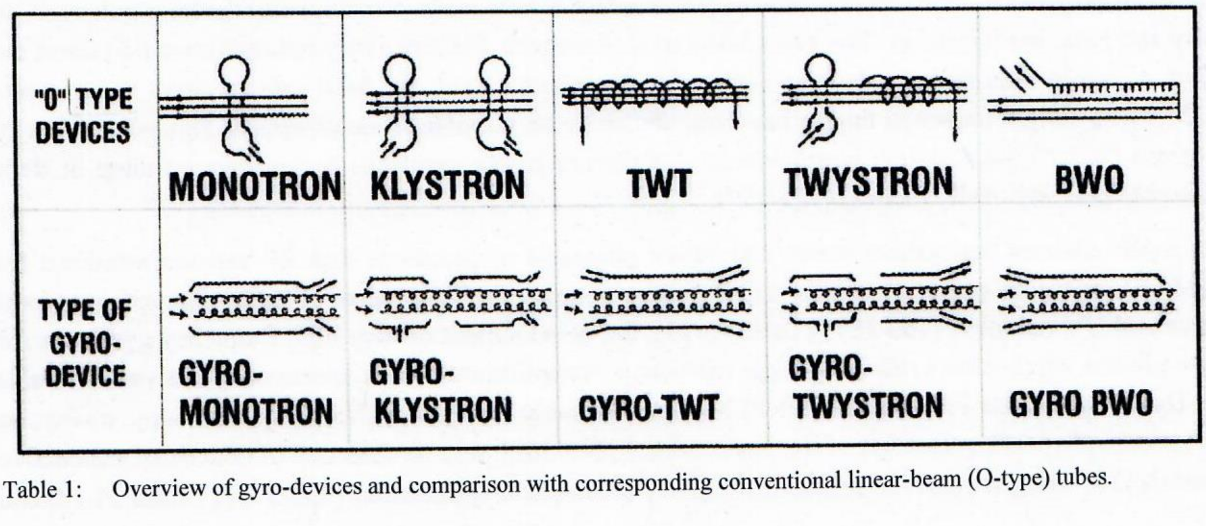


Table 1: Overview of gyro-devices and comparison with corresponding conventional linear-beam (O-type) tubes.

# 2 Gyrotron Oscillators and Microwave Vacuum Windows for Plasma Heating

| Institution | Frequency [GHz] | Mode cavity | Mode Output | Power [MW] | Efficiency [%] | Pulse length [s] |
|---|---|---|---|---|---|---|
| ABB, Baden [450,523] | 8/39 | $TE_{01}$/ $TE_{02}$ | $TE_{01}$ /$TE_{02}$ | 0.35/0.25 | 35/42 | 0.5/0.1 |
| ARIEL UNIV., Ariel [524-230] | 27,31,39,28 | $TE_{11,21,01,02}$ | $TE_{11,21,01,02}$ | 0.004-0.006 | 11-20 | ≤ 0.000011 |
| | 95/95 ($2\Omega_c$) | $TE_{02}$ | $TE_{02}$/$TEM_{00}$ | 0010/0.033 | 14/23 | 10/0.1 |
| CEERI, IPR, SAMEER, BHU, IITR, Pilani, Gandhinagar [531] | 42 | $TE_{03}$ | $TE_{03}$ | 0.126 | 20.4 | 0.0005 |
| CPI[1)], Palo Alto [15,20,532-550] | 8 | $TE_{21}$ | $TE_{10}$ | 0.5 (dual output) | 33 | 1.0 |
| | 28,35 | $TE_{02}$ | $TE_{02}$ | 0.2 | 37 | CW |
| | 53.2,56,60,70 | $TE_{01/02}$ | $TE_{02}$ | 0.23 | 37 | CW |
| | 70.15/84 | $TE_{10,3}$/ $TE_{15,4}$ | $TEM_{00}$ | 0.6/0.56 | 47/44 (SDC) | 2.25/2.0 |
| | 84 | $TE_{15,2}$ | $TE_{15,2/4}$ | 0.5 (0.9) | 28 | 0.1(0.001) |
| | 94.9 | $TE_{6,2}$ | $TEM_{00}$ | 0.12 | 50 (SDC) | CW |
| | 95.3 | $TE_{22,6}$ | $TEM_{00}$ | 0.63 (1.92) | 42 (40) (SDC) | 15 (0.005) |
| CPI[1)], NIFS, Palo Alto, Toki [87,88,535-539,551-554] | 84 | $TE_{15,3}$ | $TEM_{00}$ | 0.5(0.4)/0.1 | 29/14 | 2.0(10.5)/CW |
| | | | | 0.59(0.25) | 41(32) (SDC) | 0.001(0.2) |
| GYCOM, IAP Nizhny Novgorod [16,125,126,144-151,555-573] | 5 | $TE_{01}$ | $TE_{01}$ | 0.23 | 26 | 0.1 |
| | 25 ($2\Omega_c$) | $TE_{03}$ | $TE_{03}$ | 0.8/0.87 | 40/25(2e-beams) | 0.0001 |
| | 28 | $TE_{4,2}$/$TE_{6,2}$ | $TEM_{00}$ | 0.5 | 36 | 0.5 |
| | 37.5/44.8 | $TE_{62}$/ $TE_{15,1}$ | $TEM_{00}$/ $TE_{15,1}$ | 0.5/1.25 | 35 | 0.1/0.0001 |
| | 53.2,54.5 | $TE_{83}$ | $TEM_{00}$ | 0.5 (0.3) | 40 (36) | 0.1 (1.0) |
| | 53.5 ($3\Omega_c$) | $TE_{7,1/7,2}$ | $TE_{72}$ | 0.15 | 10 | 0.00004 |
| | 68 (70) | $TE_{93}$ | $TEM_{00}$ | 0.5 (0.68) | 50 (48) (SDC) | 1.0 (3.0) |
| | 75 | $TE_{9,4}$ /$TE_{11,5}$ | $TEM_{00}$ | 0.5/0.8 | 37/70 (SDC) | 0.1 |
| | 82.5 | $TE_{11,3}$ | $TE_{11,3}$ | 1.0 (1.5) | 50 (36) | 0.0001 |
| | 82.7/84 | $TE_{10,4}$/ $TE_{12,5}$ | $TEM_{00}$ | 0.65/0.88 (0.2) | 54 (50) (SDC) | 3.0(CW) |
| | 82.6 | $TE_{13,5}$ | $TEM_{00}$ | 1.0 | 57 (SDC) | 30 |
| low-Q cavity tunable | 64-91 | echelette | Mode | 80-200 | 11-30 | 0.0001 |
| HUGHES, Torrance [447] | 60 | $TE_{02}$ | $TE_{02}$ | 0.2 | 35 | 0.1 |
| IECAS, Beijing [574-578] | 24.1 | $TE_{01}$ | $TE_{01}$ | 0.15 | 24 | 0.02 |
| | 34.3($2\Omega_c$) | $TE_{02/03}$ | $TE_{03}$ | 0.2 | 30 | 0.02 |
| | 94 | $TE_{02}$ | $TE_{02}$ | 0.0158 | 30.3 | 120 |
| IECAS, NTHU [579, 580] | 94 | $TE_{01}$ | $TE_{01}$ | 0.008 | 9.5 | 0.1 |
| IAE-CAEP, Mianyang [581-589] | 28/50 | $TE_{02}$/$TE_{83}$/$TE_{83}$ | $TEM_{00}$ | 0.055/0.4/0.2 | 46/50/38 (SDC) | 30/5.0/3.0 |
| | 95 | $TE_{03}$/$TE_{62}$ | $TE_{03}$/$TEM_{00}$ | 0.02/0.03/12 | 20 | 10/600/CW |
| | 94($2\Omega_c$)/95($3\Omega_c$) | $TE_{02}$/$TE_{61}$ | $TEM_{11}$/$TE_{61}$ | 0.012/0.006 | 24 (SDC)/4 | 300/0.0001 |
| KERI, Changwon [590,591] | 94.5 | $TE_{6,2}$ | $TEM_{00}$ | 0.1/0.037 | 33/48 (SDC) | 0.00005/2 |
| LAP/INPE, Sao Paulo [592] | 24.2/30.4 | $TE_{12}$ /$TE_{22}$ | $TE_{12}$ /$TE_{22}$ | 0.0058/0.0063 | 16/18.5 | 0.000015 |
| MITSUBISHI, Amagasaki KYOTO UNIV. [593] | 88 | $TE_{8,2}$ | $TEM_{00}$ | 0.35 | 29 | 0.1 |
| NEC, Kawasaki [594] | 35 | $TE_{01}$ | $TE_{01}$ | 0.1 | 30 | 0.001 |
| NRL, Washington D.C. [447,595-597] | 35 | $TE_{01}$ | $TE_{01}$ | 0.15 | 31 | 0.02 |
| | 35 | $TE_{04}$($TE_{01/04}$) | $TE_{04}$ | 0.475 (0.34) | 38 (54) | 0.001 |
| | 35/85 | $TE_{24}$/$TE_{13}$ | $TE_{24}$/$TE_{13}$ | 0.43 (0.3)/0.2 | 41 (63)/30 | 0.001 |
| PHILIPS[2)], Hamburg [598] | 70 | $TE_{02}$ | $TE_{02}$ | 0.21(0.14) | 38(30) | 0.1(CW) |
| SPbSTU, St. Petersburg KIT[3)] Karlsruhe [599-606] | 74.2 | $TE_{12,3}$ | $TE_{12,3}$ | 0.1 | 44 | 0.00005 |
| THALES ED[4)], Velizy [450,607] | 8 | $TE_{5,1}$ | $TE_{5,1}$ | 1.0 | 45 | 1.0 |
| | 35 | $TE_{02}$ | $TE_{02}$ | 0.335 | 43 | 0.15 |
| TSUKUBA UNIV., QST, CANON[5)] Ibaraki, Otawara [90-92,607-622] | 28 | $TE_{02}$ | $TE_{02}$ | 0.2 | 35.7 | 0.075 |
| | 28 | $TE_{4,2}$ /$TE_{8,3}$ | $TEM_{00}$ | 1.38 (0.4) | 40 (31) | 3 (CW) |
| | 41(56) | $TE_{02}$ | $TE_{02}$ | 0.2 | 31.3 (32.9) | 0.1 |
| | 77 | $TE_{18,6}$ | $TEM_{00}$ | 1.9/1.6/1.2/0.22 | 38 (SDC) | 0.1/1.8/10/4500 |
| | 82 | $TE_{17,6}$ | $TEM_{00}$ | 1.0/0.4 | 35 (SDC) | 1/2 |
| UESTC, Chengdu [578,623-631] | 15 | $TE_{01}$ | $TEM_{00}$ | 0.1 | 30 | 0.0001 |
| | 35 ($3\Omega_c$) | $TE_{51}$/$TE_{52}$ | $TE_{52}$ | 0.147 | 10.2 | 0.0001PM, 100kg |
| | 70,94 ($2\Omega_c$) | $TE_{02}$/$TE_{03}$ | $TE_{03}$ | 0.1(0.16) | 20 (26.5) | 0.0001 |
| | 94 | $TE_{61}$/$TE_{62}$ | $TE_{62}$/$TEM_{00}$ | 0.027 (0.02) | 30 (45 (SDC)) | CW |
| | 95.3 | $TE_{22,6}$ | $TE_{22,6}$ | 0.43 | 34.7 | 0.000003 |
| UNIV. FUKUI, TOSHIBA [594] | 70 | $TE_{02}$ | $TE_{02}$ | 0.025 | 28.4 | 0.001 |
| UNIST, Ulsan [632] | 95 | $TE_{62}$ | $TEM_{00}$ | 0.062 | 22 | 0.000003 |

SDC: Single-stage Depressed Collector [1)] Communications & Power Industries, formerly VARIAN, [2)] formerly VALVO, [3)]Karlsruhe Institute of Technology, formerly FZK, [4)] TED, formerly Thomson TE, [5)] formerly TOSHIBA

Table 2: Performance parameters of gyrotron oscillators with frequencies between 5 and 95 GHz.

| Institution | Frequency [GHz] | Mode cavity | Mode output | Power [MW] | Efficiency [%] | Pulse length [s] |
|---|---|---|---|---|---|---|
| **CPI[1], Palo Alto** | 106.4($2\Omega_c$) | $TE_{02/03}$ | $TE_{03}$ | 0.135 | 21 | 0.1 |
| **[15,56,283,533-537,546-549,633-658]** | 106.4 | $TE_{12,2}$ | $TE_{12,2}$ | 0.4 | 30 | 0.1 |
| | 110 | $TE_{15,2}$ | $TE_{15,2}$ | 0.5(0.3) | 28(28) | 1.0(2.0) |
| | 110 | $TE_{22,2}$ | $TE_{22,2/4}$ | 0.5 | 27 | 2.5 |
| | 110 | $TE_{22,6}$ | $TEM_{00}$ | 1.28 | 42.3 (SDC) | 0.001 |
| | | | | 1.05 | 31 | 5.0 |
| | | | | 0.6 (0.52) | 31 (29 SDC) | 10.0 |
| | | | | 0.106 | 21 | CW |
| | 117.5 | $TE_{20,9}$ | $TEM_{00}$ | 1.67 | 37 (SDC) | 0.001 |
| | | | | 1.2/0.95/0.55 | 34 (SDC) | 0.4/5.0/10.0 |
| **KIT[2], Karlsruhe** | 117.9 | $TE_{19,5}$ | $TEM_{00}$ | 1.55 | 31 | 0.007 |
| **[127-139,659-678]** | | | | 1.55 | 49.5 (SDC) | 0.007 |
| | 132.6 | $TE_{9,4}$ | $TE_{9,4}$ | 0.42 | 21 | 0.005 |
| **GYCOM-M, IAP** | 110 | $TE_{19,5}$ | $TEM_{00}$ | 1.2 | 40 | 0.0001 |
| **Moscow, N. Novgorod** | | | | 1.0 | 65(SDC) | 0.0001 |
| **[16,452,562,679-688]** | | | | 0.93 | 36 | 2.0 |
| | | | | 0.5 | 35 | 5.0 |
| | | | | 0.35 | 33 | 10.0 |
| **GYCOM, IAP** | 100 | $TE_{22,2}$ | $TE_{22,2}$ | 1.1 | 34 | 0.0001 |
| **Nizhny Novgorod** | 104 | $TE_{18,7}$ | $TEM_{00}$ | 0.98 | 46.5 (SDC) | 0.5 |
| **[16,125,126,140-159,558-563, 689-693]** | 105 | $TE_{17,6}$ | $TEM_{00}$ | 1.04/0.85 | 57/50 (SDC) | 10/300 |
| | 106.4 | $TE_{15,4}$ | $TEM_{00}$ | 0.5 | 33 | 0.2 |
| | 110 | $TE_{15,4}$ | $TEM_{00}$ | 0.5 | 33 | 1.0 |
| | 111.5 | $TE_{19,6}$ | $TEM_{00}$ | 1.0 | 32 | 0.0001 |
| | 129 | $TE_{17,5}$ | $TEM_{00}$ | 0.5 | 32 | 0.5 |
| **QST[3], CANON[4]** | 104.1 | $TE_{19,7}$ | $TEM_{00}$ | 0.9 | 41 (SDC) | 300 |
| **Naka, Otawara [23,620-622,694-722]** | 110 | $TE_{22,2}$ | $TEM_{00}$ | 0.75 | 27.6 | 0.002 |
| | | | | 0.61 | 30 | 0.05 |
| | | | | 0.61 | 50 (SDC) | 0.05 |
| | | | | 0.42/0.35 | 48 (SDC) | 3.3/5.0 |
| | 110 | $TE_{22,6}$ | $TEM_{00}$ | 1.5 | 45 (SDC) | 4.0 |
| | | | | 1.0 | 38 (SDC) | 70 |
| | 110 | $TE_{22,8}$ | $TEM_{00}$ | 1.5/1.0 | 47/45 (SDC) | 3.8/100 |
| | 110 | $TE_{22,12}$ | $TE_{22,12}$ | 0.7 | 30 | 0.001 |
| | 120 | $TE_{03}$ | $TE_{03}$ | 0.17 | 25 | 0.01 |
| | 120 | $TE_{12,2}$ | $TE_{12,2}$ | 0.46/0.25 | 24 | 0.1/0.22 |
| | 120 | $TE_{12,2}$ | $TEM_{00}$ | 0.5 | 24 | 0.1 |
| | 137.6 | $TE_{27,10}$ | $TEM_{00}$ | 1.0 | 44 (SDC) | 100 |
| | 136.8 | $TE_{25,9}$ | $TEM_{00}$ | 1.0 | 44 (SDC) | 300 |
| **MITSUBISHI, Amagasaki** | 120 | $TE_{02/03}$ | $TE_{03}$ | 0.16 | 25 | 0.06 |
| **[723,724]** | 120 | $TE_{15,2}$ | $TE_{15,2}$ | 1.02 | 32.5 | 0.0002 |
| | | | | 0.46(0.25) | 30 | 0.1(0.21) |
| **THALES ED[5], Velizy** | 100 | $TE_{34}$ | $TE_{34}$ | 0.19 | 30 | 0.07 |
| **[450,607]** | 110 | $TE_{93}$ | $TE_{93}$ | 0.42 | 17.5 | 0.002 |
| | 110 | $TE_{64}$ | $TE_{64}$ | 0.34 | 19 | 0.01 |
| | | | | 0.39 | 19.5 | 0.21 |
| **THALES ED[5], CEA, SPC[6], KIT [725-735]** | 118 | $TE_{22,6}$ | $TEM_{00}$ | 0.7 | 37 | 0.01 |
| | | | | 0.53(0.35) | 32(23) | 5.0(111) |

SDC: Single-stage Depressed Collector
[1] Communications & Power Industries, formerly VARIAN, [2] formerly KfK, then FZK, [3] formerly JAERI, then JAEA, [4] formerly TOSHIBA [5] formerly Thomson TE, [6] formerly CRPP

Table 3: Present development status of high frequency gyrotron oscillators for ECH&CD and stability control in magnetic fusion devices (100 GHz $\leq$ f < 140 GHz, $\tau \geq$ 0.1 ms).

| Institution | Frequency [GHz] | Mode | | Power [MW] | Efficiency [%] | Pulse length [s] |
|---|---|---|---|---|---|---|
| | | cavity | Output | | | |
| **BVERI, Beijing [736-738]** | 140.2 | $TE_{22,6}$ | $TEM_{00}(TE_{22,6})$ | 0.56(0.43) | 24.5 (22.6) | 0.001 |
| | 170 | $TE_{25,10}$ | $TEM_{00}$ | 0.21 | 15.9 | 0.1 |
| **CPI[1], Palo Alto** | 140 | $TE_{02/03}$ | $TE_{03}$ | 0.1 | 27 | CW |
| **[15,20,283,533-537,546,548,549,** | 140 | $TE_{15,2}$ | $TE_{15,2}$ | 1.04(0.32) | 38 (31) | 0.0005(3.6) |
| **642-646,649-653,655-657,739-744]** | | | | 0.2 (0.4) | 31 | avg. (peak) |
| | 140.2 | $TE_{28,7}$ | $TEM_{00}$ | 0.92/0.9 | 36/33 (SDC) | 0.003/1800 |
| | 170 | $TE_{31,8}$ | $TEM_{00}$ | 1.0(0.6) | 35 (SDC) (26) | 0.002(15) |
| **IAE-CAEP, Mianyang [745,746]** | 140 | $TE_{7,3}$ | $TEM_{00}$ | 0.030/0.052 | 34/39.4 (SDC) | 60/30 |
| **IE and IPP, Hefei [747]** | 169.6 | $TE_{25,10}$ | $TEM_{00}$ | 0.35 | 16.8 | 0.015 |
| **KIT[2], PHILIPS[3] [450,748]** | 140.8 | $TE_{03}$ | $TE_{03}$ | 0.12 | 26 | 0.4 |
| **KIT[2], Karlsruhe** | 140.2 | $TE_{10,4}$ | $TE_{10,4}$ | 0.69 | 28 | 0.005 |
| **[127-139,451,659-678,748-764]** | 140.2 | $TE_{10,4}$ | $TEM_{00}$ | 0.6(0.5) | 27 (32) | 0.012(0.03) |
| | | | | 0.50 | 48 (SDC) | 0.03 |
| | 140.5 | $TE_{10,4}$ | $TEM_{00}$ | 0.46 | 51 (SDC) | 0.2 |
| | 140.1 | $TE_{22,6}$ | $TEM_{00}$ | 1.6/2.1 | 60/53 (SDC) | 0.007/0.001 |
| | 150 | $TE_{03}$ | $TE_{03}$ | 0.12 | 20 | 0.0005 |
| | 162.3 | $TE_{25,7}$ | $TEM_{00}$ | 1.48 | 35(50 (SDC) | 0.007 |
| **KIT[2], SPC[4], THALES ED[5],** | 139.8 | $TE_{28,8}$ | $TEM_{00}$ | 1.0/0.92 | 50/44 (SDC) | 12/1800 |
| **[6,7,70-82,95-104,728,765-809]** | 140.3 | $TE_{28,10}$ | $TEM_{00}$ | 1.7/1.5 | 43/45 (SDC) | 0.001 |
| **EGYC[6] [810-824]** | 170 | $TE_{32,9}$ | $TEM_{00}$ | 1.5 | 33/50 (SDC) | 0.001 |
| | | | | 0.96/0.56/0.47 | 38/41 (SDC) | 1000/485/1570 |
| **GYCOM, IAP** | 140 | $TE_{22,6}$ | $TEM_{00}$ | 0.96 | 36 | 1.2 |
| **Nizhny Novgorod** | | | | 0.54 | 36 | 3.0 |
| **[16,140-159,483,559-563,681-688,** | | | | 0.26 (0.1) | 36 | 10 (80) |
| **693,825-803]** | | (dual-beam | output) | 2x0.37 | 30 | 3.0 |
| | | | | 2x0.3 | 29 | 5.5 |
| | | | | 2x0.165 | 28 | 10.0 |
| | 140 | $TE_{22,8}$ | $TEM_{00}$ | 1.7 | 42 | 0.0001 |
| | | | | 1.2 | 68 (SDC) | 0.0001 |
| | 140 | $TE_{22,8}$ | $TEM_{00}$ | 1.14/0.95/0.7 | 59/52/49(SDC) | 10/300/3000 |
| | 170 | $TE_{25,10}$ | $TEM_{00}$ | 1.2/0.96 | 53/57 (SDC) | 100/1000 |
| | 170 | $TE_{28,12}$ | $TEM_{00}$ | 1.75/1.5/1.2 | 53/47 (SDC) | 0.1/2.3/500 |
| | 250 | $TE_{19,8}$ | $TEM_{00}$ | 330/90 | 30 | 0.000045/1 |
| **GYCOM-N, IAP** | 140 | $TE_{22,6}$ | $TEM_{00}$ | 0.8 | 32 | 0.8 |
| **Nizhny Novgorod** | | | | 0.88 | 50.5 (SDC) | 1.0 |
| **[16,125,126,558-560,563,567,** | | | | 0.55 | 33 | 2.0 |
| **686-689,691,692,825,840,864-870]** | 140 | $TE_{22,10}$ | $TEM_{00}$ | 0.99 | 47 (SDC) | 0.5 |
| | 151 echelette | $TE_{0,18}$ | $TE_{0,18}$ | 0.9 | 32 | 0.00005 |
| | 158.5 | $TE_{24,7}$ | $TEM_{00}$ | 0.5 | 30 | 0.7 |
| | 169.9 | $TE_{7,3}$ | $TEM_{00}$ | 0.02 | 27 | 30 (driver) |
| **QST[7], CANON[8]** | 170 | $TE_{22,6}$ | $TEM_{00}$ | 0.45 | 19 | 0.05 |
| **Naka, Otawara** | | | | 0.25 | 32 (SDC) | 0.4 |
| **[23,700-715,871-917]** | 170.1 | $TE_{31,8}$ | $TE_{31,8}$ | 1.15 | 29 | 0.0004 |
| | 170 | $TE_{31,8}$ | $TEM_{00}$ | 1.3/1.2 | 32/57 (SDC) | 0.003 |
| | | | | 1.0/0.8 | 55/57 (SDC) | 800/3600 |
| | 170 | $TE_{31,12}$ | $TEM_{00}$ | 1.56(0.94) | 27 | 0.001(50) |
| | 170 | $TE_{31,11}$ | $TEM_{00}$ | 1.23/1.05/0.6 | 47/51/46 (SDC) | 2.0/300/1000 |
| **QST[7], TSUKUBA UNIV., CANON[8] [620-622,918-921]** | 300 | $TE_{32,18}$ | $TE_{32,18}$ | 0.52/0.62 | 20 | 0.002/0.001 tilted $SiO_2$ window |
| **NIFS, TSUKUBA UNIV., CANON[8]** | 154 | $TE_{28,8}$ | $TEM_{00}$ | 1.25 | 37 (SDC) | 0.004 |
| **Toki, Ibaraki, Otawara** | | | | 0.35 | 39 (SDC) | 1800 |
| **[87-90,554,616,618-622,922-924]** | 168 | $TE_{31,8}$ | $TEM_{00}$ | 0.52 | 19 | 1.0 |
| | | | | 0.52 | 30 (SDC) | 1.0 |

SDC: Single-stage Depressed Collector [1] Comm. & Power Industries, formerly VARIAN, [2] formerly KfK, then FZK, [3] formerly VALVO, [4] formerly SPC, [5] formerly Thomson TE, [6] EGYC collaboration among SPC, Switzerland; KIT, Germany; HELLAS, Greece; CNR, Italy; ENEA Italy, [7] formerly JAERI, then JAEA, [8] formerly TOSHIBA

Table 4: Present development status of high frequency gyrotron oscillators for ECH&CD and stability control in magnetic fusion devices (f ≥ 140 GHz, τ ≥ 0.1 ms).

| Institution | Frequency [GHz] | Mode cavity | Mode output | Power [MW] | Efficiency [%] | Corrug. Cavity inner | Corrug. Cavity outer |
|---|---|---|---|---|---|---|---|
| **KIT[1] Karlsruhe** | 137.78 | $TE_{27,16}$ | $TE_{27,16}$ | 1.03 | 24.3 | yes | no |
| **[6,23,26-29,98-100,759-765,** | 139.96 | $TE_{28,16}$ | $TE_{28,16}$ | 1.17 | 27.2 | yes | no* |
| **781,925-944]** | | | $TE_{76,2}/TEM_{00}$ | 0.95 | 20 | yes | no |
| **Pulse length ≤ 10 ms** | | | | 0.95 | 29 (SDC) | yes | no |
| | | | | (dual beam output) | | | |
| | 142.02 | $TE_{29,16}$ | $TE_{29,16}$ | 1.04 | 24.4 | yes | no |
| | 138.70 | $TE_{27,14}$ | $TEM_{00}$ | 1.14 | 26.1 | yes | no |
| | 146.70 | $TE_{28,15}$ | $TEM_{00}$ | 1.13 | 25.6 | yes | no |
| | 156.90 | $TE_{30,16}$ | $TEM_{00}$ | 1.24 | 25.4 | yes | no |
| | 164.98 | $TE_{31,17}$ | $TE_{31,17}$ | 1.17 | 26.7 | yes | no |
| | | | $TEM_{00}$ | 2.2 | 28 | yes | no |
| | | | | (single-beam output) | | | |
| | | | | 1.5 | 30 | yes | no |
| | | | | 1.5 | 48 (SDC) | yes | no |
| | 167.14 | $TE_{32,17}$ | $TEM_{00}$ | 1.22 | 25.6 | yes | no |
| **EGYC[2], KIT[1][26-30,101-112,945-982]** | 170 | $TE_{34,19}$ | $TEM_{00}$ | 2.1(1ms) | 48 (SDC) | yes | no |
| **Pulse length ≤ 100 ms** | | | | 2.1/1.5 (11/35ms) | 47/42 (SDC) | yes | no |
| **IAP, Nizhny Novgorod** | 45 | $TE_{15,1}$ | $TE_{15,1}$ | 1.25 | 43 | no | no |
| **[14,16,559,562,983-991]** | 100 | $TE_{21,18}$ | $TE_{21,18}$ | 1.0 | 35 | yes | no |
| **Pulse length ≤ 0.1 ms** | | | | 0.5 | 20 | no | no |
| | 100 | $TE_{20,13}$ | $TE_{20,13}$ | 2.1 | 30 | no | no |
| | | | | 1.6 | 38 | no | no |
| | 103 | $TE_{22,13}$ | $TE_{22,13}$ | 1.0 | 40 | yes | yes |
| | | | | 0.7 | 30 | yes | no |
| | | | | 0.3 | 14 | no | no |
| | 107 | $TE_{17,7}$ | $TE_{17,7}$ | 0.7 | 25 | no | no |
| | 110 | $TE_{20,13}$ | $TE_{20,13}$ | 1.15 | 35 | yes | no |
| | 110 | $TE_{21,13}$ | $TE_{21,13}$ | 1.0 | 35 | yes | no |
| | 140 | $TE_{28,16}$ | $TE_{28,16}$ | 1.5 | 33.5 | yes | no* |
| | | | | 1.15 | 50 (SDC) | yes | no |
| | | | $TE_{76,2}$ | 1.17 | 35.2 | yes | yes |
| | | | $TEM_{00}$ | 1.1 | 30 | yes | no |
| | | | | (dual-beam output) | | | |
| | 224 ($2\Omega_c$) | $TE_{33,8}$ | $TE_{33,8}$ | 0.1 | 11 | yes | no |
| **IAP, KIT[1] Karlsruhe [925]** | 133 | $TE_{27,15}$ | $TE_{27,15}$ | 1.3 | 29 | no | no |
| **Pulse length 30 μs** | 140 | $TE_{28,16}$ | $TE_{28,16}$ | 1.0 | 23 | no | no |
| **MIT, Cambridge [992-995]** | 137 | $TE_{25,11}$ | $TEM_{00}$ | 0.5 | 7.5 | no | no |
| **Pulse length 3 μs** | 139.6 | $TE_{26,11}$ | $TEM_{00}$ | 0.9 | 13 | no | no |
| | 142.2 | $TE_{27,11}$ | $TEM_{00}$ | 1.0 | 14.5 | no | no |
| | 140 | $TE_{21,13}$ | $TEM_{00}$ | 0.5 | 7.5 | no | no |
| **UESTC, Chengdu [996]** | 110/220 ($2\Omega_c$) two electron beams | $TE_{02}/TE_{04}$ | $TEM_{00}$ | 0.02 | 5 | no | no |

1) formerly KfK, then FZK, * very similar cavity and tube design
2) EGYC is a collaboration among CRPP (now SPC), Switzerland; KIT, Germany; HELLAS, Greece; CNR, Italy; ENEA Italy

Table 5: Present experimental development status of short pulse (3 μs – 50 ms) coaxial cavity gyrotron oscillators.

Design studies on 4 MW, 170 GHz and 2 MW, 240 GHz coaxial-cavity gyrotrons for future fusion reactors were performed at KIT [997-1000]. The 4 MW tube would operate in the $TE_{52,31}$-mode and its q.o. output coupler would generate two 2 MW fundamental Gaussian beams which leave the tube through two CVD-diamond windows.

| Institution | Frequency [GHz] | Mode cavity | Mode output | Power [MW] | Efficiency [%] | Pulse length [s] |
|---|---|---|---|---|---|---|
| **CPI[1], Palo Alto** | 8 | TE$_{21}$ | TE$_{10}$ | 0.4 | 26.6 | 0.0005 |
| **[27,30,532-550,637-646,649-658, 739-744]** | (dual rectangular waveguide output) | | | 0.4 | 34.2 (SDC) | 0.0005 |
| | 70.15 | TE$_{10,3}$ | TEM$_{00}$ | 0.6 | 47 (SDC) | 2.25 |
| | 94.9 | TE$_{62}$ | TEM$_{00}$ | 0.12 | 50 (SDC) | CW |
| | 95.3 | TE$_{22,6}$ | TEM$_{00}$ | 0.62 (1.92) | 41(40) (SDC) | 15 (0.005) |
| | 110 | TE$_{22,6}$ | TEM$_{00}$ | 1.28 | 42.3 (SDC) | 0.001 |
| | | | | 0.52 | 29 (SDC) | 10 |
| | 140.2 | TE$_{27,8}$ | TEM$_{00}$ | 0.92/0.9 | 36/33 (SDC) | 0.003/1800 |
| **IAE-CAEP, Mianyang [581-589,745,746]** | 28 | TE$_{0,2}$ | TEM$_{00}$ | 0.05 | 46 (SDC) | 30 |
| | 140 | TE$_{7,3}$ | TEM$_{00}$ | 0.030/0.052 | 34/39.4 (SDC) | 60/30 |
| **CPI[1], NIFS** | 84 | TE$_{15,3}$ | TEM$_{00}$ | 0.5 | 29 | 2.0 |
| **Palo Alto, Toki [87-90,538]** | | | | 0.59 | 41 (SDC) | 0.001 |
| | | | | 0.25 | 32 (SDC) | 0.2 |
| **KIT[2], Karlsruhe** | 117.9 | TE$_{19,5}$ | TEM$_{00}$ | 1.55 | 49.5 (SDC) | 0.007 |
| **[24,127-134,659-678,754-765]** | 140.2 | TE$_{10,4}$ | TEM$_{00}$ | 0.50/0.46 | 48/51(SDC) | 0.03/0.2 |
| | 140.1 | TE$_{22,6}$ | TEM$_{00}$ | 1.6/2.1 | 60/53 (SDC) | 0.007/0.001 |
| | 162.3 | TE$_{25,7}$ | TEM$_{00}$ | 1.48 | 50 (SDC) | 0.007 |
| **KIT[2], SPC[3], EGYC, THALES ED[4],** | 139.8 | TE$_{28,8}$ | TEM$_{00}$ | 1.0/0.92 | 50/44 (SDC) | 12/1800 |
| **[7,27,30,71-75,98-113,728,765-824]** | 140.3 | TE$_{28,10}$ | TEM$_{00}$ | 1.5 | 45 (SDC) | 0.001 |
| | 170 | TE$_{32,9}$ | TEM$_{00}$ | 0.96 | 37 (SDC) | 1000 |
| **GYCOM, IAP** | 68 (70) | TE$_{9,3}$ | TEM$_{00}$ | 0.5 (0.68) | 50 (48) (SDC) | 1.0 (3.0) |
| **Nizhny Novgorod** | 75 | TE$_{11,5}$ | TEM$_{00}$ | 0.8 | 70 (SDC) | 0.1 |
| **[560-562,565-568,573,682,683,688,690]** | 82.7 | TE$_{10,4}$ | TEM$_{00}$ | 0.65/0.2 | 38/52 (SDC) | 3.0/CW |
| | 82.6 | TE$_{13,5}$ | TEM$_{00}$ | 1.0 | 57 (SDC) | 30 |
| | 84 | TE$_{12,5}$ | TEM$_{00}$ | 0.88 (0.2) | 50 (SDC) | 3.0 (CW) |
| | 104 | TE$_{18,7}$ | TEM$_{00}$ | 0.98 | 46.5 (SDC) | 0.5 |
| | 110 | TE$_{19,5}$ | TEM$_{00}$ | 1.0 | 65 (SDC) | 0.0001 |
| | 140 | TE$_{22,6}$ | TEM$_{00}$ | 0.8/0.88 | 32/50.5 (SDC) | 0.8/1.0 |
| | 140 | TE$_{22,10}$ | TEM$_{00}$ | 0.99 | 47 (SDC) | 0.5 |
| **GYCOM, IAP** | 140 | TE$_{22,8}$ | TEM$_{00}$ | 1.7 | 42 | 0.0001 |
| **Nizhny Novgorod** | | | | 1.14/0.95/0.7 | 59/52/49 (SDC) | 10/300/1000 |
| **[27,30,140-159,567,829-861,864]** | 170 | TE$_{25,10}$ | TEM$_{00}$ | 1.2 | 53 (SDC) | 100 |
| | | | | 0.96 | 57 (SDC) | 1000 |
| | 170 | TE$_{28,12}$ | TEM$_{00}$ | 1.75/1.5/1.2 | 53/47 (SDC) | 0.1/2.5/500 |
| **KERI, Changwon [590,591]** | 94.5 | TE$_{6,2}$ | TEM$_{00}$ | 0.1/0.037 | 33/48 (SDC) | 0.00005/2 |
| **NRL, Washington D.C.** | 115 | QOG | TEM$_{00}$ | 0.43 | 12.7 (SDC) | $10^{-5}$ |
| **[1001]** | | | | 0.20 | 16.1 (SDC) | $10^{-5}$ |
| **QST[5], CANON[6]** | 104.1 | TE$_{19,7}$ | TEM$_{00}$ | 0.9 | 41 (SDC) | 300 |
| **Naka, Otawara** | 110 | TE$_{22,2}$ | TEM$_{00}$ | 0.61/0.35 | 50/48 (SDC) | 0.05/5.0 |
| **[27,30,697-722,871-917,920,921]** | 110 | TE$_{22,6}$ | TEM$_{00}$ | 1.5 | 45 (SDC) | 4.0 |
| | | | | 1.0 | 38 (SDC) | 70 |
| | 110 | TE$_{22,8}$ | TEM$_{00}$ | 1.5/1.0 | 47/45 (SDC) | 3.8/100 |
| | 136.8 | TE$_{25.9}$ | TEM$_{00}$ | 1.0 | 44 (SDC) | 300 |
| | 138 | TE$_{27,10}$ | TEM$_{00}$ | 1.0 | 43 (SDC) | 100 |
| | 170 | TE$_{22,6}$ | TEM$_{00}$ | 0.25 | 19/32 (SDC) | 0.4 |
| | 170.2 | TE$_{31,8}$ | TEM$_{00}$ | 1.2 | 57 (SDC) | 0.003 |
| | | | | 1.0 | 55 (SDC) | 800 |
| | | | | 0.8 | 57 (SDC) | 3600 |
| | 170 | TE$_{31,11}$ | TEM$_{00}$ | 1.23/1.05/0.6 | 47/51/46 SDC | 2.0/300/1000 |
| **NIFS, TSUKUBA UNIV., CANON[6]** | 77 | TE$_{18,6}$ | TEM$_{00}$ | 1.9 | 38 (SDC) | 0.1 |
| **Toki, Ibaraki, Otawara** | | | | 1.8/1.6/1.2/0.22 | 38 (SDC) | 0.1/1.8/10/4500 |
| **[27,30,87-92,554,611-622,921-924]** | 154 | TE$_{28,8}$ | TEM$_{00}$ | 1.25(0.35) | 39 (SDC) | 0.004 (1800) |
| | 168 | TE$_{31,8}$ | TEM$_{00}$ | 0.52 | 19 | 1.0 |
| | | | | 0.52 | 30 (SDC) | 1.0 |

SDC: Single-stage Depressed Collector; QOG: Quasi-Optical Gyrotron, EGYC: Cons. among SPC, Swisse; KIT, Germany; HELLAS, Greece; CNR, Italy; ENEA Italy [1] formerly VARIAN, [2] formerly KfK, then FZK, [4] formerly CRPP, [4] formerly Thomson TE, [5] formerly JAERI, then JAEA, [6] formerly TOSHIBA

Table 6: Present development status of high frequency gyrotron oscillators with conventional cylindrical or quasi-optical cavity and single-stage depressed collector (SDC) ($\tau \geq 10$ μs).

| Institution | Frequency [GHz] | Mode cavity | Mode output | Power [MW] | Efficiency [%] | Pulse length [s] | |
|---|---|---|---|---|---|---|---|
| KIT[1)], Karlsruhe | 114.2 | $TE_{18,5}$ | $TEM_{00}$ | 0.85 | 23 | 0.001 | |
| [27-30,127-139,664,667, | 117.9 | $TE_{19,5}$ | $TEM_{00}$ | 1.0 | 27 | 0.001 | |
| 669-678] | | | | 1.55 | 49.5 (SDC) | 0.007 | optimized |
| | 121.6(119.5) | $TE_{20,5}(TE_{19,7})$ | $TEM_{00}$ | 1.0(0.88) | 27(23) | 0.001 | |
| | 125.3(124.1) | $TE_{21,5}(TE_{20,7})$ | $TEM_{00}$ | 1.0(1.0) | 27(33.0) | 0.001 | |
| | 128.9(127.5) | $TE_{22,5}(TE_{21,7})$ | $TEM_{00}$ | 0.9(1.04) | 24.5(35.0) | 0.001 | |
| | 132.6(130.9) | $TE_{20,6}(TE_{22,7})$ | $TEM_{00}$ | 0.85(0.9) | 23(24) | 0.001 | |
| | 136.2 | $TE_{21,6}$ | $TEM_{00}$ | 0.9 | 24.5 | 0.001 | |
| | 140.1(140.0) | $TE_{22,6}(TE_{22,8})$ | $TEM_{00}$ | 1.0(1.2) | 27(37.0) | 0.001 | |
| | | | | 1.6 | 60 (SDC) | 0.007 | optimized |
| | 143.7(143.4) | $TE_{23,6}(TE_{23,8})$ | $TEM_{00}$ | 1.1(1.2) | 30(40.7) | 0.001 | |
| | 147.4(146.7) | $TE_{24,6}(TE_{24,8})$ | $TEM_{00}$ | 1.1(1.2) | 30(41.8) | 0.001 | |
| | 151.2 | $TE_{25,6}$ | $TEM_{00}$ | 1.05 | 28.5 | 0.001 | |
| | 154.9(155.9) | $TE_{23,7}(TE_{24,9})$ | $TEM_{00}$ | 0.95(0.98) | 26(26) | 0.001 | |
| | 158.5(159.2) | $TE_{24,7}(TE_{25,9})$ | $TEM_{00}$ | 1.1(1.1) | 30(32.1) | 0.001 | |
| | 162.3(162.5) | $TE_{25,7}(TE_{26,9})$ | $TEM_{00}$ | 1.0(1.2) | 27(36.9) | 0.001 | |
| | | | | 1.48 | 50 (SDC) | 0.007 | optimized |
| | 166.0(165.9) | $TE_{26,7}(TE_{27,9})$ | $TEM_{00}$ | 1.0(1.1) | 26(31.9) | 0.001 | |
| | (169.2) | $(TE_{28,9})$ | $TEM_{00}$ | (1.15) | (35.7) | 0.001 | |
| GYCOM, IAP | 71.5 | $TE_{10,5}$ | $TEM_{00}$ | 0.8 | 56 | 0.15 | |
| Nizhny Novgorod | 74.8 | $TE_{11,5}$ | $TEM_{00}$ | 0.8 | 56 | 0.15 | |
| [27-30,125,126,140-159, | 78.1 | $TE_{12,5}$ | $TEM_{00}$ | 0.8 | 56 | 0.15 | |
| 562,564-567,688,1002] | 105.1 | $TE_{17,6}$ | $TEM_{00}$ | 1.24 | 41.2 | 0.0001 | |
| | 111.7 | $TE_{19,6}$ | $TEM_{00}$ | 1.37 (0.8) | 42.9 (30) | 0.0001(0.1) | |
| | 124.3 | $TE_{20,7}$ | $TEM_{00}$ | 1.18(0.85) | 37(29) | 0.0001(10) | |
| | 127.6 | $TE_{21,7}$ | $TEM_{00}$ | 1.33 | 41.6 | 0.0001 | |
| | 140.1 | $TE_{22,8}$ | $TEM_{00}$ | 1.42 (1.7) | 43.3 (42) | 0.0001 | |
| | 152.6 | $TE_{23,9}$ | $TEM_{00}$ | 1.44 | 44.2 | 0.0001 | |
| | 156.0 | $TE_{24,9}$ | $TEM_{00}$ | 1.01 | 36.1 | 0.0001 | |
| | 104 | $TE_{18,7}$ | $TEM_{00}$ | 0.98 | 46.5 (SDC) | 0.5 | |
| | 140 | $TE_{22,10}$ | $TEM_{00}$ | 0.99 | 47 (SDC) | 0.5 | |
| QST[2)], CANON[3)] | 166.7 | $TE_{30,8}$ | $TEM_{00}$ | 0.54 | 27 | 0.001 | plane window |
| Naka, Otawara | 170 | $TE_{31,8}$ | $TEM_{00}$ | 0.62 | 32 | 0.001 | plane window |
| [27,30,892,1004] | | | | | | | |
| QST[2)], TSUKUBA, | 225.96 | $TE_{26,13}$ | $TE_{26,13}$ | 0.274 | 18.1 | 0.002 | plane window |
| CANON[3)] | 228.13 | $TE_{24,14}$ | $TE_{24,14}$ | 0.285 | 18.8 | 0.002 | plane window |
| Naka, Ibaraki, Otawara | 242.1 | $TE_{25,15}$ | $TE_{25,15}$ | 0.288 | 18.9 | 0.002 | plane window |
| [30,919,920] | 243.9 | $TE_{28,14}$ | $TE_{28,14}$ | 0.345 | 22.8 | 0.002 | plane window |
| | 250.04 | $TE_{27,15}$ | $TE_{27,15}$ | 0.292 | 19.3 | 0.002 | plane window |
| | 253.99 | $TE_{28,15}$ | $TE_{28,15}$ | 0.310 | 20.5 | 0.002 | plane window |
| | 295.65 | $TE_{31,18}$ | $TE_{31,18}$ | 0.54 | 19.3 | 0.002 | plane window |
| | 299.84 | $TE_{32,18}$ | $TE_{32,18}$ | 0.52 | 19.3 | 0.002 | plane window |
| | 301.8 | $TE_{30,19}$ | $TE_{30,19}$ | 0.52 | 19.3 | 0.002 | plane window |
| MIT, Cambridge | 107.1 | $TE_{21,6}$ | $TEM_{00}$ | 1.1 | 30 | 0.000003 | plane window |
| [1005-1014] | 110.1 | $TE_{22,6}$ | $TEM_{00}$ | 1.4 | 37 | 0.000003 | plane window |
| | 113.0 | $TE_{23,6}$ | $TEM_{00}$ | 1.1 | 30 | 0.000003 | plane window |
| | 124.5 | $TE_{24,7}$ | $TEM_{00}$ | 1.0 | 24 | 0.000003 | plane window |

SDC: Single-stage Depressed Collector; [1)] formerly KfK, then FZK, [2)] formerly JAERI, then JAEA, [3)] formerly TOSHIBA

Table 7: Step-tunable 1 MW-class gyrotrons at KIT with Quartz, Silicon Nitride (Kyocera SN-287) or CVD-diamond Brewster window. The GYCOM 140 GHz TE22,10-mode tube was also operated in 50-150 ms pulses with a BN Brewster window (11 frequencies at 0.8 MW between 104 and 143 GHz). The QST and MIT gyrotrons used a plane single-disk output window.

IAP Nizhny Novgorod operated a 40 μs short-pulse gyrotron in 10 modes starting from $TE_{12,4}$ at 133.9 GHz with 38 kW output power up to $TE_{19,8}$ at 249.5 GHz with 183 kW and efficiencies from 10 to 27 % [1003].

| Institution | Frequency [GHz] | Mode cavity | Mode output | Power [MW] | Efficiency [%] | Pulse length [s] | No. of Frequencies |
|---|---|---|---|---|---|---|---|
| CPI, Palo Alto [657] | 104 | $TE_{22,5}$ | $TEM_{00}$ | 0.52 | 30 (SDC) | 0.005 | 2f-Gyrotron |
| | 140 | $TE_{28,7}$ | $TEM_{00}$ | 0.81 | 37 (SDC) | 600 | 2f-Gyrotron |
| KIT[1)], SPC[2)] EGYC[3)], THALES ED[4)] [27-30,782,1015,1016] | 84 | $TE_{17,5}$ | $TEM_{00}$ | 0.97 | 31 | 1.1 | 2f-Gyrotron |
| | 126 | $TE_{26,7}$ | $TEM_{00}$ | 1.03 | 31 | 1.2 | 2f-Gyrotron |
| | 103.8 | $TE_{21,6}$ | $TEM_{00}$ | 0.41 | 27 (SDC) | 10 | 2f-Gyrotron |
| | 140.0 | $TE_{28,8}$ | $TEM_{00}$ | 0.92 | 44 (SDC) | 1800 | 2f-Gyrotron |
| GYCOM, IAP | 121.5 | $TE_{20,5}$ | $TEM_{00}$ | 0.5 | 30 | 0.1 | 3f-Gyrotron |
| Nizhny Novgorod | 140.0 | $TE_{22,6}$ | $TEM_{00}$ | 0.5 | 30 | 0.5 | 3f-Gyrotron |
| [27-30,40-55,142-159,563, | 158.5 | $TE_{24,7}$ | $TEM_{00}$ | 0.5 | 30 | 0.7 | 3f-Gyrotron |
| 567,688, 691-693,841-861, | 105.1 | $TE_{17,6}$ | $TEM_{00}$ | 1.04/0.85 | 59/50 (SDC) | 10/300 | 2f-Gyrotron |
| 1002,1017] | 140.1 | $TE_{22,8}$ | $TEM_{00}$ | 1.14/095 | 57/52 (SDC) | 10/300 | 2f-Gyrotron |
| | 134.7 | $TE_{20,8}$ | $TEM_{00}$ | 0.78 | 42.2 (SDC) | 0.1 | 2f-Gyrotron |
| | 170 | $TE_{25,10}$ | $TEM_{00}$ | 0.96 | 58 (SDC) | 1000 | 2f-Gyrotron |
| IAE-CAEP, Mianyang | 105.1 | $TE_{18,7}$ | $TEM_{00}$ | 0.71 | 34.0 (SDC) | 0.001 | 2f-Gyrotron |
| [1018-1020] | 139.4 | $TE_{24,9}$ | $TEM_{00}$ | 1.06 | 49.0 (SDC) | 0.001 | 2f-Gyrotron |
| QST[5)], CANON[6)] | 104.1 | $TE_{19,7}$ | $TEM_{00}$ | 0.9 | 41 (SDC) | 300 | 4f-Gyrotron |
| Naka, Otawara | 136.8 | $TE_{25,9}$ | $TEM_{00}$ | 1.0/ | 44 (SDC) | 300 | 4f-Gyrotron |
| [27,30,892,895,897-912, | 170 | $TE_{31,11}$ | $TEM_{00}$ | 1.2/1.0/0.6 | 47/46/46 SDC | 5/300/2000 | 4f-Gyrotron |
| 915,917,1004,1021-1023] | 203 | $TE_{37,13}$ | $TEM_{00}$ | 1.0/0.6 | 50 (SDC) | 3/10 | 4f-Gyrotron |
| QST[5)], CANON[6)] | 82 | $TE_{17,6}$ | $TEM_{00}$ | 1.0/0.4 | 35 (SDC) | 1/2 | 3f-Gyrotron |
| Naka, Otawara | 110 | $TE_{22,8}$ | $TEM_{00}$ | 1.9/1.5/1.0 | 47/45 (SDC) | 1/5.0/100 | 3f-Gyrotron |
| [622,716-722] | 137.6 | $TE_{27,10}$ | $TEM_{00}$ | 1.9/1.3/1.0 | 43 (SDC) | 1/1.3/100 | 3f-Gyrotron |
| NIFS, TSUKUBA UNIV., | 28.04 | $TE_{8,5}$ | $TEM_{00}$ | 1.65 | 31 | 0.002 | 2f-Gyrotron |
| CANON[6)] | 34.83 | $TE_{10,6}$ | $TEM_{00}$ | 1.21 | 27 | 0.002 | 2f-Gyrotron |
| Toki, Ibaraki, Otawara | 115.5 | $TE_{21,7}$ | $TEM_{00}$ | | | | 2f-Gyrotron |
| [620,621,722,920-923,1024] | 154 | $TE_{28,9}$ | $TEM_{00}$ | | | | 2f-Gyrotron |

SDC: Single-stage Depressed Collector; [1)] formerly KfK, then FZK, [2)] formerly CRPP, [3)] EGYC collaboration among SPC, Switzerland; KIT, Germany; HELLAS, Greece; CNR, Italy; ENEA Italy, [4)] formerly Thomson TE, [5)] formerly JAERI, then JAEA, [6)] formerly TOSHIBA

Table 8: Multi-frequency gyrotrons operating at different transmission maxima of a plane single-disk window.

The KIT 1 MW $TE_{22,6}$-mode gyrotron operated at frequencies between 114 and 166 GHz has been investigated with respect to fast-frequency tunability in the frequency range from 132.6 to 147.4 GHz [133]. For that purpose, the gyrotron has been equipped with a special hybrid-magnet system consisting of superconducting (sc) magnets in the cryostat and additional normal-conducting (nc) copper magnets with a fast time constant at cavity and cathode. Special problems due to the magnetic coupling between the different magnets were investigated by calculation and experiment. Making use of these investigations different current regulation schemes for the nc magnets were implemented and tested experimentally. Finally, megawatt-class step-tuning operation between the five $TE_{m,6}$-modes ($m = 20 - 24$) from $TE_{20,6}$ to $TE_{24,6}$ in time steps of 1 s has been achieved.

The Japan 1 MW ITER gyrotron was operated in a fast-tunable (3.5 s) sc magnet (JASTEC) at 170 GHz ($TE_{31,8}$, 615 kW, 32%) and 167 GHz ($TE_{30,8}$, 538 kW, 27%). The efficiencies are without SDC [1004].

| Institution | Frequency [GHz] | Mode cavity | Mode output | Power [MW] | Efficiency [%] | Pulse length [s] |
|---|---|---|---|---|---|---|
| **IAP, Nizhny Novgorod [14,15]** | 103.8 | $TE_{16,7}$ | $TE_{16,7}$ | 0.5 | 17.9 | 0.0001 |
| | 107 | $TE_{17,7}$ | $TE_{17,7}$ | 0.7 | 25 | 0.0001 |
| | 110.2 | $TE_{18,7}$ | $TE_{18,7}$ | 0.6 | 21.5 | 0.0001 |
| **KIT[1)], Karlsruhe [132,933-936,939-941]** | 136.3 | $TE_{26,14}$ | $TEM_{00}$ | 1.02 | 23.5 | 0.001 |
| | 138.7 | $TE_{27,14}$ | $TEM_{00}$ | 1.14 | 26.1 | 0.001 |
| | 140.8 | $TE_{28,14}$ | $TEM_{00}$ | 0.92 | 24.0 | 0.001 |
| | 142.2 | $TE_{26,15}$ | $TEM_{00}$ | 0.90 | 20.6 | 0.001 |
| | 144.4 | $TE_{27,15}$ | $TEM_{00}$ | 0.96 | 23.1 | 0.001 |
| | 146.7 | $TE_{28,15}$ | $TEM_{00}$ | 1.13 | 25.6 | 0.001 |
| | 149.0 | $TE_{29,15}$ | $TEM_{00}$ | 1.08 | 22.9 | 0.001 |
| | 151.1 | $TE_{30,15}$ | $TEM_{00}$ | 1.00 | 21.3 | 0.001 |
| | 152.4 | $TE_{28,16}$ | $TEM_{00}$ | 0.75 | 20.8 | 0.001 |
| | 154.6 | $TE_{29,16}$ | $TEM_{00}$ | 0.94 | 23.4 | 0.001 |
| | 156.9 | $TE_{30,16}$ | $TEM_{00}$ | 1.24 | 25.4 | 0.001 |
| | 159.2 | $TE_{31,16}$ | $TEM_{00}$ | 1.04 | 23.9 | 0.001 |
| | 160.7 | $TE_{29,17}$ | $TEM_{00}$ | 0.99 | 20.7 | 0.001 |
| | 162.8 | $TE_{30,17}$ | $TEM_{00}$ | 0.98 | 20.7 | 0.001 |
| | 165.1 | $TE_{31,17}$ | $TEM_{00}$ | 1.24 | 26.3 | 0.001 |
| | | | | 1.24 | 41 (SDC) | 0.001 |
| | 167.2 | $TE_{32,17}$ | $TEM_{00}$ | 1.22 | 25.6 | 0.001 |
| **EGYC[2)] [964-968,971,974]** | 141.3 | $TE_{28,16}$ | $TEM_{00}$ | 1.8 | 26 | 0.001 |
| | 170.0 | $TE_{34,19}$ | $TEM_{00}$ | 2.2 | 30 | 0.001 |

SDC: Single-stage Depressed Collector;
[1)] formerly KfK, then FZK, [2)] EGYC is a collaboration among CRPP (now SPC), Switzerland; KIT, Germany; HELLAS, Greece; CNR, Italy; ENEA Italy

Table 9: Step-tunable 1 MW and 2 MW gyrotrons with coaxial cavity. IAP: Smooth inner rod and plane output window disk. KIT and EGYC: Tapered and longitudinally corrugated inner rod and broadband Silicon Nitride (Kyocera SN-287) Brewster window.

A specific feature of the coaxial gyrotron design is that it allows electron beam energy recovery and very fast frequency tuning via biasing the coaxial insert [987-990]. By biasing the inner rod of the KIT coaxial-cavity gyrotron, such very fast (within $\approx$ 0.1 ms) frequency tuning was demonstrated at a power level of 1 MW. In particular, fast step frequency tuning between the 165.1 GHz nominal mode and its azimuthal neighbors at 162.8 GHz and 167.2 GHz (see Table 9) was obtained. In addition, operating in the nominal $TE_{31,17}$-mode, continuous frequency pulling within 70 MHz bandwidth was achieved [940].

| Material | Type | Power (kW) | Frequency (GHz) | Pulse Length (s) | Institution |
|---|---|---|---|---|---|
| Water-Free Fused Silica | single-disk inertially cooled | 200 | 60 | 5.0 | UKAEA/Culham |
| Boron Nitride | single-disk water edge cooled | 930 | 110 | 2.0 | IAP/GYCOM |
| | | 350 | 110 | 10.0 | IAP/GYCOM |
| | | 960 | 140 | 1.2 | IAP/GYCOM |
| | | 550 | 140 | 3.0 | IAP/GYCOM |
| | | 100 | 140 | 80.0 | IAP/GYCOM |
| | | 1030 | 170 | 1.0 | IAP/GYCOM |
| | | 500 | 170 | 5.0 | IAP/GYCOM |
| | | 270 | 170 | 10.0 | IAP/GYCOM |
| Silicon Nitride | single-disk gas face and water edge cooled | 130 | 84 | 30.0 | NIFS/CPI |
| | | 520 | 168 | 1.0 | NIFS/CANON[1)] |
| Sapphire | single-disk $LN_2$ edge cooled | 530 | 118 | 5.0 | CEA/SPC/KIT/THALES |
| | | 350 | 118 | 100 | CEA/SPC/KIT/THALES |
| | | 285* | 140 | 3.0 | IAP/INFK |
| | | 500 | 140 | 0.5 | KIT/IAP/IGVP/IPP |
| | | 370 | 140 | 1.3 | KIT/IAP/IGVP/IPP |
| Sapphire | single-disk LHe edge cooled | 410 | 110 | 1.0 | QST/CANON[1)] |
| | | 500 | 110 | 0.5 | QST/GA |
| Sapphire | double-disk FC75 face cooled | 200 | 28 | CW | CPI |
| | | 200 | 35 | CW | CPI |
| | | 200 | 60 | CW | CPI |
| | | 400 | 84 | 10.5 | NIFS/CPI |
| | | 350 | 110 | 5.0 | QST/CANON[1)] |
| | | 200 | 140 | CW | CPI |
| | | 500 | 170 | 0.6 | QST/CANON[1)] |
| Sapphire | distributed water cooled | 65** | 110 | 0.3 | GA/QST |
| | | 200* | 110 | 0.7 | GA/CPI |
| Au-Doped Silicon | single-disk $CO_2$ gas edge cooled | 600 | 140 | 0.8 | IAP/GYCOM |
| CVD-Diamond | single-disk water edge cooled | 400 | 28 | CW | TSUKUBA/CANON[1)] |
| | | 600 | 70 | 2.3 | CPI |
| | | 1.2 | 77 | 10 | NIFS/TSUKUBA/CANON[1)] |
| | | 0.3 | 77 | CW | NIFS/TSUKUBA/CANON[1)] |
| | | 500 | 84 | 2.0 | CPI |
| | | 100 | 94 | CW | CPI |
| | | 300 | 104 | 20 | QST/CANON[1)] |
| | | 300** | 110 | 1.0 | CPI/FOM |
| | | 50 | 110 | CW | CPI/FOM |
| | | 450 | 110 | 2.0 | IAP/GYCOM/GA |
| | | 1050 | 110 | 5.0 | CPI/GA |
| | | 600 | 110 | 10 | CPI/GA |
| | | 1500 | 110 | 4.0 | QST/CANON[1)] |
| | | 1000 | 110 | 70 | QST/CANON[1)] |
| | | 340 | 118 | 50 | KIT/CEA/THALES |
| | | 300 | 118 | 111 | KIT/CEA/THALES |
| | | 300 | 137 | 250 | QST/CANON[1)] |
| | | 1000 | 140 | 12 | KIT/SPC/TED |
| | | 920 | 140 | 1800 | KIT/SPC/TED |
| | | 900 | 140 | 1800 | CPI |
| | | 950/700 | 140 | 200/1000 | IAP/GYCOM |
| | | 350 | 154 | 1800 | NIFS/TSUKUBA/CANON[1)] |
| | | 1500 | 170 | 2.5 | IAP/GYCOM |
| | | 1200 | 170 | 100 | IAP/GYCOM |
| | | 1000 | 170 | 1000 | IAP/GYCOM |
| | | 1000 | 170 | 800 | QST/CANON[1)] |
| | | 800 | 170 | 3600 | QST/CANON[1)] |
| | | 600 | 203 | 10 | QST/CANON[1)] |

Note:* and ** indicates that the power corresponds to that of a 1 MW (*) and 0.8 MW (**) $HE_{11}$ mode, [1)] formerly TOSHIBA

Table 10: Experimental parameters of high-power millimeter-wave vacuum windows [15,16,20,23-30,144-159, 450-452, 534-550,554,562,567,568,611-623,633-744,769-921,1004,1015-1074].

| Material | BeO<br>p.c. | BN (CVD)<br>p.c. | $Si_3N_4$ composite (SN-287) | Sapphire ($Al_2O_3$)<br>s.c.<br>orientation of E<br>$c \perp \vec{E}$ | Silicon Au-doped<br>s.c. | Diamond (PACVD)<br>p.c. | Si C (6 H)<br>p.c. |
|---|---|---|---|---|---|---|---|
| Thermal Conductivity 300 K<br>k [W/mK] 500 K | 260 | 55 | 59 | 40<br>6 | 150 | 2000<br>1100 | 330 |
| Ultimate Bending Strength<br>$\sigma_B$ [MPa] | 140 | 80 | 800 | 410 | 1000 | Growth 450<br>Nucleation 800 | 440 |
| Poissons Number<br>$\nu$ | 0.3 | 0.25 | 0.28 | 0.22 | 0.1 | 0.1 | 0.18 |
| Density<br>$\rho$ [g/cm³] | 2.85 | 2.3 | 3.4 | 4.0 | 2.3 | 3.515 | 3.2 |
| Specific Heat Capacity<br>$c_p$ [J/g K] | 1.05 | 0.8 | 0.6 | 0.8 | 0.7 | 0.502 | 0.38 |
| Young's Modulus<br>E [GPa] | 345 | 70 | 320 | 385 | 190 | 1050 | 700 |
| Therm. Expans. Coeff.<br>$\alpha$ [$10^{-6}$/K] | 7.2 | 3 | 2.4 | 5.5 | 2.5 | 1.0 | 4.3 |
| Permittivity (145 GHz)<br>$\varepsilon_r'$ | 6.7 | 4.7 | 7.84 | 9.4 | 11.7 | 5.67 | 9.92 |
| Loss Tangent (145 GHz)<br>$\tan\delta$ [$10^{-5}$] | 70 | 115 | 30 | 20 | 0.35 | 2 | 7 |
| Metallizing and Brazing<br>Bakeout Temperature | o.k. | o.k. | o.k.<br>550°C | o.k.<br>550°C | o.k<br>550°C | o.k.<br>450°C | o.k.<br>550°C |
| Possible Size ∅ [mm] | 150 | 145 | 300 | 270 | 127 | 120 | |
| Cost | medium | medium | high | high | low | very high | medium |
| Failure Resistance R' [W/mm²]<br>$R' = k\sigma_B (1-\nu)/E\alpha$ | 10.3 | 15.7 | 44.5 | 6.0 | 284 | 772 | 40 |
| RF-Power Capacity $P_T$ [100W²s/mm⁴K]<br>$P_T = R'\rho\, c_p/((1+\varepsilon_r')\tan\delta)$ | 0.06 | 0.05 | 0.36 | 0.09 | 106 | 106 | 0.63 |
| Radiation Sensitivity<br>n($10^{20}$-$10^{21}$n/m²)<br>γ/X (0.75 Gy/s) | | | | no<br>no | no<br>no | no<br>no | |

Table 11: Thermophysical, mechanical and dielectrical parameters of window materials related to thermal load-failure resistance and power transmission capacity of edge-cooled windows at room temperature (p.c. = poly-crystalline, s.c. = single-crystalline) [95,118,1046,1052,1059,1061,1069-1073,1075-1079].

| Material | Sapphire ($Al_2O_3$) s.c. orientation of E c⊥ $\vec{E}$ | Silicon Au-doped s.c. | Diamond (PACVD) p.c. |
|---|---|---|---|
| Thermal Conductivity k [W/mK] | 900 (20000) | 1300 | 10000 |
| Ultimate Bending Strength $\sigma_B$ [MPa] | 410 | 1000 | 450 |
| Poissons Number $\nu$ | 0.22 | 0.1 | 0.1 |
| Density $\rho$ [g/cm³] | 4.0 | 2.3 | 3.52 |
| Specific Heat Capacity $c_p$ [J/g K] | 0.8 | 0.7 | 0.52 |
| Young's Modulus E [GPa] | 402 (405) | 190 | 1050 |
| Therm. Expans. Coeff. $\alpha$ [$10^{-6}$/K] | 5.5 | 2.5 | 1.2 |
| Permittivity (145 GHz) $\varepsilon_r'$ | 9.3 | 11.5 | 5.67 |
| Loss Tangent (145 GHz) $\tan\delta$ [$10^{-5}$] | 0.57 (0.2) | 0.35 | 2 |
| Metallizing and Brazing Bakeout Temperature | o.k. 550°C | o.k 550°C | o.k. 450°C |
| Possible Size ∅ [mm] | 270 | 127 | 160 |
| Cost | high | low | very high |
| Failure Resistance R' [W/mm²] $R' = k\sigma_B(1-\nu)/E\alpha$ | 130 (2871) | 2463 | 3214 |
| RF-Power Capacity $P_T$ [100W²s/mm⁴K] $P_T = R'\rho c_P/((1+\varepsilon_r')\tan\delta)$ | 71 (4460) | 907 | 441 |
| Radiation Sensitivity n(0.3 · $10^{21}$n/m²) γ/X (0.75 Gy/s) | no no | no no | no no |

Table 12: Thermophysical, mechanical and dielectrical parameters of window materials related to thermal load-failure resistance and power transmission capacity of edge-cooled windows at LN2-temperature – 77 K (LNe-Temperature – 30 K) (p.c. = poly-crystalline, s.c. = single-crystalline) [1046].

| | Material | Type | RF-Profile | Cross-Section | Cooling |
|---|---|---|---|---|---|
| ① | Sapphire/Metal | distributed | flattened Gaussian | rectangular (100 mm x 100 mm) | internally water cooled (300 K) $\tan\delta = 2\text{-}5 \cdot 10^{-4}$, k = 40 W/mK |
| ② | Diamond | single-disk | Gaussian | circular (∅ = 80 mm) | water edge cooled (300 K) $\tan\delta = 2 \cdot 10^{-5}$, k = 1900 W/mK |
| ③ | Diamond | single-disk Brewster | Gaussian | elliptical (152 mm x 63.5 mm) | water edge cooled (300 K) $\tan\delta = 2 \cdot 10^{-5}$, k = 1900 W/mK |
| ④ | Silicon Au-doped | single-disk | Gaussian | circular (∅ = 80 mm) | edge cooled (230 K), refrigerator $\tan\delta = 2.5 \cdot 10^{-6}$, k = 300 W/mK |
| ⑤ | Silicon Au-doped | single-disk | Gaussian | circular (∅ = 80 mm) | $LN_2$ edge cooled (77 K) $\tan\delta = 4 \cdot 10^{-6}$, k = 1500 W/mK |
| ⑥ | Sapphire | single disk | flattened Gaussian | elliptical (285 mm x 35 mm) | $LN_2$ edge cooled (77 K) $\tan\delta = 6.7 \cdot 10^{-6}$, k = 1000 W/mK |
| ⑦ | Sapphire | single disk | Gaussian | circular (∅ = 80 mm) | LNe or LHe edge cooled (27 K) $\tan\delta = 1.9 \cdot 10^{-6}$, k = 2000 W/mK |

Note that the power capability of options ②,③,⑤ and ⑦ is even 2 MW.

Table 13: Options for 1 MW, CW, 170 GHz gyrotron windows [93-98,118,1046].

First operation of a wideband short-pulse D-band megawatt gyrotron with elliptically brazed CVD-diamond Brewster window was published in [135-137]. A CVD-diamond Brewster window in corrugated $HE_{11}$-waveguide with 32 mm inner diameter was tested at 110 GHz using 0.5 s pulses with powers up to 350 kW [1080-1082]. Broadband CVD-diamond Brewster windows are also developed for use in gyro-amplifiers [1083,1084].

# 3 Harmonic and Very High Frequency Gyrotron Oscillators

| Institution | Frequency [GHz] | Mode | Power [kW] | Efficiency [%] | Pulse length [ms] |
|---|---|---|---|---|---|
| CPI[1)], Palo Alto [1085] | 250 | $TE_{11,1}/TE_{11,2}$ | 10 | 3.4 | 0.1 |
| IAP, N. Novgorod [188,189,1086-1089] | 157 | $TE_{03}$ | 2.4 | 9.5 | CW |
| | 250 | $TE_{02}/TE_{65}$ | 4.3/1 | 18/5 | CW |
| | 326 | $TE_{23}$ | 1.5 | 6.2 | CW |
| | 526 | $TE_{65}$ | 0.25 | 2.7 | CW |
| | 1228 | $TE_{58,13}$ | 50 | 10 | 0.03 |
| MIT, Cambridge [1090-1092] | 209 | $TE_{92}$ | 15 | 3.5 | 0.001 |
| | 241 | $TE_{11,2}$ | 25 | 6.5 | 0.001 |
| | 302 | $TE_{34}$ | 4 | 1.5 | 0.0015 |
| | 339 | $TE_{10,2}$ | 4 | 3 | 0.0015 |
| | 363 | $TE_{11,2}$ | 7 | 2.5 | 0.0015 |
| | 417 | $TE_{10,3}$ | 15 | 6 | 0.0015 |
| | 457/467 | $TE_{15,2}/TE_{12,3}$ | 7/22 | 2/3.5 | 0.0015 |
| | 503 | $TE_{17,2}$ | 10 | 5.5 | 0.0015 |
| UESTC, Chengdu [1093-1102] | 390.9 | $TE_{16}$ | 1.5 | 2.4 | 0.004 |
| | 403.9/412.2 | $TE_{64}/TE_{93}$ | 2.1/1.2 | 3.3/2.4 | 0.004 |
| | 416.4 | $TE_{45}$ | 3 | 4.9 | 0.004/0.004 |
| | 421.65 | $TE_{17,3}/TE_{17,4}$ | 19.3 | 8.6 | 0.004 |
| | 423.1 | $TE_{26}$ | 8(1.15) | 5.2 | 0.04 |
| | 446.1 | $TE_{55}$ | 5 | 5.4 | 0.004(5) |
| | 679 | $TE_{15,2}$ | 3.25 | 9.3 | 0.1 |
| UNIVERSITY, Fukui [205-218,220-225,1103-1117] | 203.4 | $TE_{33}$ | 1.6 | 16 | CW |
| | 350.3 | $TE_{65}$ | 52 | 8.3 | 0.003 |
| | 384[*)] | $TE_{26}$ | 3 | 3.7 | 1 |
| | 388 | $TE_{18}/TE_{17,2}$ | 62/83 | 158/13.8 | 0.003 |
| | 392.6 | $TE_{85}$ | 60 | 9.6 | 0.004 |
| | 402[*)] | $TE_{55}$ | 2 | 3 | 1 |
| | 576[*)] | $TE_{26}$ | 1 | 2.5 | 0.5 |
| | 874[*)] | $TE_{19}$ | 0.6 | 2.0 | 0.5 |

[1)] Communications & Power Industries; formerly VARIAN [*)] In collaboration with TOSHIBA, Ottawara

Table 14: Performance parameters of mm- and submillimeter-wave gyrotrons operating at the 2nd harmonic of the electron cyclotron frequency, with output power > 0.6 kW.

| Institution | Frequency [GHz] | Mode | Harmonic No. s | Power [kW] | Efficiency [%] | Pulse length [ms] |
|---|---|---|---|---|---|---|
| UNIVERSITY, Fukui | 84.9 | $TE_{31}$ | 3 | 2.5 | 6.3 | 1 |
| IAP, Nizhny Novgorod | 89.3 | $TE_{31}$ | 3 | 1.7 | 3.3 | 1 |
| [1118-1121] | 112.7 | $TE_{41}$ | 4 | 0.47 | 1 | 1 |
| | 138.0 | $TE_{51}$ | 5 | 0.1 | 0.2 | 1 |
| IAP, Nizhny Novgorod [195-204,1122-1134] | 267 | $TE_{25}$ | 2 | 0.9 | 4 | CW |
| | 394 | $TE_{37}$ | 3 | 0.37 | 1.6 | CW |
| | 550 | $TE_{24}$ | 2 | 0.6 | 2.2 | 0.01 |
| | | | 2 (sectioned klystron-type cavity) | 0.5 | 1 | 0.01 |
| | 680 | $TE_{25}$ | 2 | 1.8 | 3.5 | 0.01 |
| | 740 | $TE_{35}$ | 3 | 0.25 | 0.6 | 0.01 |
| | | | 3 (sectioned klystron-type cavity) | 0.2 | 0.55 | 0.01 |
| | 870 | $TE_{36}$ | 3 | 0.3 | 0.9 | 0.01 |
| | 1000 | $TE_{37}$ | 3 | 0.4 | 0.7 | 0.01 |
| | 1300 | $TE_{37}$ | 3 | 1.3 | 2.4 | 0.01 |

Table 15: Operation results of high harmonic gyrotrons with axis-encircling electron beam (LOG) and permanent magnet (Nd Fe B) at University of Fukui and pulsed magnet at IAP (THz gyrotron).

| Institution | Frequency [GHz] | Mode | Power [MW] | Efficiency [%] | Pulse length [μs] | |
|---|---|---|---|---|---|---|
| IAP, | 250 | $TE_{20,2}$ | 0.3 | 31 | 30 - 80 | pulsed magnetic field |
| Nizhny Novgorod | 304 | $TE_{22,8}$ | 0.3 | 25 | 25 | |
| [188-194,196-204,338,363,364,1135-1138] | 330 | | 0.13 | 17 | 30 - 80 | |
| | 430 | | 0.12 | 9 | 30 – 80 | |
| | 500 | $TE_{28,3}$ | 0.1 | 8.2 | 30 – 80 | |
| | 540 | | 0.06 | 5 | 30 – 80 | |
| | 600/650 | $TE_{38,2}$ | 0.05/0.04 | 5/3.5 | 30 – 80 | |
| | 530/670 | $TE_{31,8}$ | 0.20/0.21 | 22/20 | 20 | |
| | 1002 | $TE_{68}$ | 0.0018 | 2.4 | 40 | |
| | 1024 | $TE_{17,4}$ | 0.005 | 6.1 | 40 | |
| | 1300 | $TE_{24,4}$ | 0.0005 | 0.6 | 40 | |
| | 263.2 | $TE_{5,3}$ | 0.001 | 17 | CW | CW operation |
| MIT, Cambridge | 107.1 | $TE_{21,6}$ | 0.94 | 24 | 3 | |
| [124,993,1005-1014,1139-1154] | 110 | $TE_{22,6}$ | 1.67 | 42 | 3 | |
| | | $TEM_{00}$ | 1.5 | 48 (SDC) | 3 | output mode parity 96% |
| | 113.2 | $TE_{23,6}$ | 1.18 | 30 | 3 | |
| | 140 | $TE_{04}$-like | 0.025 | 7.4 | 3 | PBG resonator, BW = 35% |
| | 140 | $TE_{15,2}$ | 1.33 | 40 | 3 | |
| | 148 | $TE_{16,2}$ | 1.3 | 39 | 3 | |
| | 166.6 | $TE_{27,8}$ | 1.50 | 34 | 3 | |
| | 170.0 | $TE_{28,8}$ | 1.50 | 35 | 3 | |
| | 173.4 | $TE_{29,8}$ | 0.72 | 29 | 3 | |
| | 188 | $TE_{18,3}$ | 0.6 | | 3 | |
| | 225 | $TE_{23,3}$ | 0.37 | | 3 | |
| | 231 | $TE_{38,5}$ | 1.2 | 20 | 3 | |
| | 236 | $TE_{21,4}$ | 0.4 | | 3 | |
| | 267 | $TE_{28,4}$ | 0.2 | | 3 | |
| | 280 | $TE_{25,13}$ | 0.78 | 17 | 3 | |
| | 287 | $TE_{22,5}$ | 0.537 | 19 | 3 | |
| | 320 | $TE_{29,5}$ | 0.4 | 20 | 3 | |
| | 327 | $TE_{27,6}$ | 0.375 | 13 | 3 | |
| UESTC, Chengdu [1095,1155-1158] | 201.5 | $TE_{23}$ | 0.015 | 6.0 | 4 | |
| | 216.4 | $TE_{23}$ | 0.032 | 12.5 | 4 | |
| | 221 | $TE_{03}$ | 0.04/0.012/0.003 | 17.3/4.4/5.5 | 4 | slotted cavity/ 0.1 W with cold cath-ode |
| | 228.6 | $TE_{52}$ | 0.025 | 14.9 | 4 | |
| UNIVERSITY, Fukui | 202.9 | $TE_{33}$ | 0.001 | 10 | 10000 | |
| [27,223,226-241,1104-1107,1159] | 278 | $TE_{33}$ | 0.001 | 5 | 1000 | |
| | 290 | $TE_{62}$ | 0.001 | 4 | 1000 | |
| | 294 | $TE_{14,2}$ | 0.246 | 27 | 40 | $TEM_{00}$ output mode |
| | 303.3 | $TE_{22,2}$ | 0.32 | 32.8 | 100 | |
| | 314 | $TE_{43}$ | 0.001 | 4 | 1000 | |

Table 16: Performance parameters of pulsed and CW millimeter- and submillimeter- wave gyrotron oscillators operating at the fundamental electron cyclotron resonance.

Operating at the fundamental, the 2nd harmonic or the 3rd harmonic of the electron cyclotron frequency, with one or two electron beams, enables the gyrotron to act as a medium power (several 1-100 W) step tunable, mm- and sub-mm wave source in the frequency range from 38 GHz (fundamental) to 1.014 THz ($TE_{4,12}$-mode, 2nd harmonic) [205-362,1159-1169].

A 30 W two-cavity gyrotron with frequency multiplication achieved at IAP an efficiency of 0.43 %. The first cavity operated in the $TE_{01}$ mode near the fundamental cyclotron frequency at 95 GHz, the output cavity oscillated at the 3rd harmonic 285 GHz in the $TE_{03}$-mode [1170-1174]. Simultaneous generation at the 2nd (37.5 GHz) and 4th (75 GHz) harmonic (140 W at 60 kV and 6A) was obtained by a self-excited gyromultiplier with single, sectioned cavity [1175,1176]. A high-harmonic sectioned $TE_{35}$-mode gyrotron of IAP Nizhny Novgorod produced 0.5 kW at 740 GHz with 0.9% efficiency [1177-1180].

| Institution | Frequency [GHz] | Mode | Voltage [kV] | Current [A] | Power [MW] | Efficiency [%] |
|---|---|---|---|---|---|---|
| MIT, Cambridge [1062,1063] | 187.7 | $TE_{32,4}$ | 94 | 57 | 0.65 | 12 |
| | 201.6 | $TE_{35,4}$ | 97 | 54 | 0.92 | 18 |
| | 209.5 | $TE_{33,5}$ | 98 | 37 | 0.54 | 15 |
| | 213.9 | $TE_{34,5}$ | 95 | 51 | 0.89 | 18 |
| | 218.4 | $TE_{35,5}$ | 90 | 44 | 0.56 | 14 |
| | 224.3 | $TE_{33,6}$ | 91 | 60 | 0.90 | 17 |
| | 228.8 | $TE_{34,6}$ | 92 | 59 | 0.97 | 18 |
| | | | 100 | 59 | 1.2 | 20 |
| | 265.7 | $TE_{39,7}$ | 90 | 57 | 0.64 | 12 |
| | 283.7 | $TE_{43,7}$ | 92 | 35 | 0.33 | 10 |
| | 291.6 | $TE_{41,8}$ | 93 | 54 | 0.887 | 18 |

Table 17: Step tuning of MIT gyrotron oscillators (with large MIG [1140,1141]) operating at the fundamental electron cyclotron resonance frequency (pulse length 1.5 μs).

| Institution | Frequency [GHz] | Mode | Voltage [kV] | Current [A] | Power [MW] | Efficiency [%] |
|---|---|---|---|---|---|---|
| MIT, Cambridge [1062,1063] | 249.6 | $TE_{24,11}$ | 71 | 41 | 0.39 | 14 |
| | 257.5 | $TE_{23,12}$ | 87 | 41 | 0.33 | 9 |
| | 267.5 | $TE_{25,12}$ | 85 | 33 | 0.35 | 12 |
| | 277.2 | $TE_{27,12}$ | 78 | 42 | 0.45 | 14 |
| | 280.1 | $TE_{25,13}$ | 92 | 51 | 0.78 | 17 |
| | 285.2 | $TE_{26,13}$ | 93 | 41 | 0.42 | 11 |
| | 282.8 | $TE_{23,14}$ | 94 | 39 | 0.54 | 15 |
| | 287.9 | $TE_{24,14}$ | 94 | 51 | 0.64 | 14 |
| | 292.9 | $TE_{25,14}$ | 95 | 41 | 0.72 | 18 |
| | 302.7 | $TE_{27,14}$ | 96 | 43 | 0.27 | 7 |

Table 18: Step tuning of MIT gyrotron oscillator (with small MIG [1140,1141]) operating at the fundamental electron cyclotron resonance frequency (pulse length 1.5 μs).

# 4 Gyrotrons for Technological Applications

| Institution | Frequency [GHz] | Mode cavity | Mode output | Power [kW] | Efficiency [%] | Voltage [kV] | Magnet |
|---|---|---|---|---|---|---|---|
| CPI[1)], Palo Alto [15,20,1085] | 28 | $TE_{02}$ | $TE_{02}$ | 15 | 38 | 40 | room temp. |
| | 28 (2$\Omega_c$) | $TE_{02}$ | $TE_{02}$ | 10.8 | 33.6 | 30 | room temp. |
| | 60 | $TE_{02}$ | $TE_{02}$ | 30 | 38 | 40 | cryo. mag. |
| CPI, NIFS [87-89,551-554] Palo Alto, Toki | 84 | $TE_{15,3}$ | $TEM_{00}$ | 50 | 14 | 80 | cryo. mag. |
| GYCOM/IAP, Nizhny Novgorod [1,16,126,146,179-181,376-379,382, 387-401,405-410,559,825,826,1086, 1181-1201] | 12.5 (BW=4.2 %) | $TE_{21}$ | $TE_{21}$ | 9 - 1 | 22.5-2.5 | 20 | room temp. |
| | 13(15) | $TE_{01}$ | $TE_{01}$ | 0.3(4) | 20(50) | 25(15) | room temp. |
| | 24.1 (2$\Omega_c$) | $TE_{11}$ | $TE_{11}$ | 3.5 | 23 | 12 | room temp. |
| | 24.1 (2$\Omega_c$) | $TE_{21}$ | $TE_{11}$ | 3.4 | 23 | 15 | PM, 116kg |
| | 24.1 | $TE_{32}$ | $TE_{32}$ | 36 | 50 | 33 | room temp. |
| | 24.1 (2$\Omega_c$) | $TE_{12}$ | $TE_{12}$ | 13 | 50 | 25 | room temp. |
| | | | | 28 | 32 | 25 | room temp. |
| | | | | 6.5 | 60 (SDC) | 17.5 | room temp. |
| | 28/30 (2$\Omega_c$) | $TE_{02}$ | $TE_{02}$ | 10 | 42 | 26 | room temp. |
| | | | | 30 | 35 | 26 | room temp. |
| | 28.1/28.7 (2$\Omega_c$) | $TE_{03}/TE_{23}$ | $TE_{03}/TE_{23}$ | 10 | 20 | 23-24 | 2 kHz frequency switching |
| | 28.25 (2$\Omega_c$) | $TE_{12}$ | $TE_{12}$ | 12 | 20 | 25 | PM, 68 kg[2)] |
| | 31.8-34.8 | $TE_{11}$ | $TE_{11}$ | 1.2 | 40 | 12 | mech. tun. |
| | 35.5-37.5 | $TE_{01}$ | $TE_{01}$ | 0.5 | 15.3 | 16 | mech. tun. |
| | 35.15 | $TE_{02}$ | $TE_{02}$ | 9.7 | 43 | 25 | cryo. mag. |
| | 35 | $TE_{02}$ | $TEM_{00}$ | 10-50 | 30-40 | 25-30 | cryo. mag. |
| | 37.5 | $TE_{62}$ | $TEM_{00}$ | 20 | 35 | 30 | cryo. mag. |
| | 40.5 (3$\Omega_c$) | $TE_{03}$ | $TE_{03}$ | 3.0 | 8 | 20 | room temp. |
| | 45 | $TE_{63}$ | $TEM_{00}$ | 26 | 49 | 25 | LF cryo.mag. |
| | 68-72 | $TE_{13}$ | $TE_{13}$ | 1.4 | 22 | 17.5 | mech. tun. |
| | 83 | $TE_{93}$ | $TEM_{00}$ | 10-50 | 30-40 | 25-30 | cryo. mag. |
| | 150 | $TE_{03}$ | $TE_{03}$ | 22 | 30 | 40 | cryo. mag. |
| | 157 (2$\Omega_c$) | $TE_{03}$ | $TE_{03}$ | 2.4 | 9.5 | 18 | cryo. mag. |
| | 191.5 (2$\Omega_c$) | | | 0.55 | 6.2 | 22 | cryo. mag. |
| | 250 (2$\Omega_c$) | $TE_{02}$ | $TE_{02}$ | 4.3 | 18 | 20 | cryo. mag. |
| | 250 (2$\Omega_c$) | $TE_{65}$ | $TE_{65}$ | 1 | 5 | 20 | cryo. mag. |
| | 326 (2$\Omega_c$) | $TE_{23}$ | $TE_{23}$ | 1.5 | 6 | 20 | cryo. mag. |
| KIT, Karlsruhe [1202] | 28 (2$\Omega_c$) | $TE_{12}$ | $TE_{12}$ | 22.5 | 43 | 23.4 | room temp. |
| MICRAMICS, San Jose [1203] | 24.1 (2$\Omega_c$) | $TE_{22}$ | $TEM_{mixed}$ | 5 | 25 | 23 | room temp. |
| | | | $TE_{22}$ | 10 | 25 | 23 | room temp. |
| MITSUBISHI, Amagasaki [404,1204-1206] | 28 (2$\Omega_c$) | $TE_{02}$ | $TE_{02}$ | 10 | 38.7 | 21 | PM, 600 kg[2)] tapered B |
| UESTC, Chengdu [1207] | 37.5 | $TE_{13}$ | $TE_{13}$ | 57 (0.4 average) | 9 | 50.5 | room temp. |
| UNIV. Fukui, IAP Nizhny Novgorod/ GYCOM [381,1208-1215] | 300 | $TE_{22,8}$ | $TEM_{00}$ | 2.3 | 16.4 | 14 | cryo. mag. |

[1)] Communications & Power Industries, formerly VARIAN, [2)] PM: permanent magnet

Table 19: Performance of present CW gyrotron oscillators for technological applications.

IAP Nizhny Novgorod and GYCOM have developed a dual-frequency materials processing system employing a 15 kW, 28 GHz gyrotron and a 2.5 kW, 24.1 GHz tuneable gyro-BWO (see Table 33) [382,393,394]. This system has been installed at the University of Fukui, Japan.

# 5 Relativistic Gyrotrons

| Institution | Frequency [GHz] | Mode | Voltage [MV] | Current [kA] | Power [MW] | Efficiency [%] | Type |
|---|---|---|---|---|---|---|---|
| IAP, Nizhny Novgorod | 9.23 | $TE_{01}$ | 0.27 (0.28) | 0.12 (0.06/0.045) | 10 (8/7) | 30 (45/50) | |
| [1216-1230] | 20 | $TM_{01}$ | 0.5 | 0.7 | 40 | 11.4 | |
| | 30 | $TE_{53}$ | 0.31 | 0.08/0.07 | 12/10 | 50 | |
| | 30 (35) | $TE_{53}$ ($TE_{63}$) | 0.38 | 0.11 | 20 | 50 | |
| | 35.2 | $TE_{4,2}$ | 0.55 | 2 | 110 | 10 | explos. cath.+ kicker |
| | | $TE_{7,3}$ | | | | | injection locking |
| | 53.5 ($2\Omega_c$) | $TE_{1,5}$ | 0.260 | 0.013 | 1.2 | 35 | |
| | 55.0 ($2\Omega_c$) | $TE_{6,3}$ | 0.242 | 0.014 | 1.3 | 38 | |
| | 55.7 ($2\Omega_c$) | $TE_{11,2}$ | 0.22 | 0.0325 | 2 | 28 | |
| | 79-107 | $TM_{1n}$ | 0.5 | 2-6.5 | 30 | 3-1 | slotted echelette cavity, n = 3-10 |
| | 94.4 | $TE_{12,5}$ | 0.24 | 0.103 | 5.6 | 23 | $TEM_{00}$ output and counter rotating input for injection locking |
| IAP, Nizhny Novgorod | 10 | $TE_{13}$ | 0.3 | 0.4 | 25 | 20 | slotted cavity |
| Lebedev/General Phys. Inst. Moscow | 10 | $TE_{13}$ | 0.3 | 1.0 | 60 | 15 | plasma-filled slotted cavity |
| [1218,1231-1233] | 40 | $TE_{13}$ | 0.4 | 1.3 | 25 | 5 | slotted cavity |
| KIPT, Kharkov [1234] | 12 | $TE_{13}$ | 0.12 | 8.0 | 60 | 6.3 | plasma filled slotted cavity |
| UNIV. Michigan | 2.88 | $TE_{01}^{r}$ | 0.8 | 2 (7) | 20 | 1.3 (0.4) | small orbit |
| [1235-1241] | | | 0.8 | 0.35 (1.2) | 6 | 2.1 (0.06) | large orbit |
| | 2.15 | $TE_{10}^{r}$ | 0.8 | 0.35 (1.2) | 14 | 5.0 (0.15) | large orbit |
| | 2.5 | $TE_{11}^{c}$ (coax.) | 0.8 | 0.8 (4.0) | 90 | 14 (2.8) | large orbit, slotted cavity |
| | | | | | 40 | | non-slotted cavity |
| | | | | | 20 | | non-slott. coax. cavity |
| | 10 | $TE_{11}$ | 0.4 | 0.025 | 0.6 | 6 | |
| NRL, Washington D.C. | 8.35-13 | 4-5 modes | 3.3 | 80 | 1000 | 0.4 | superradiant |
| [1242-1245] | 35 | $TE_{62}$ | 0.78 | 1.6 (3.5) | 100 | 8 (4) *) | |
| | | | 1.15 | 2.5 | 275 | 10 | |
| | 35 | $TE_{13}$ | 0.9 | 0.65 | 35 | 6 | slotted cavity |
| NUDT Changsha [1246] | 10.3 | $TE_{01}$ (coaxial) | 0.3 | 0.5 | 11 | 7.3 | carbon fiber array cathode |
| Tomsk Polytech. Inst. [1247] | 3.1 | | 0.75 | 8.0 (30) | 1800 | 8 | also vircator interaction |
| UNIV. Niigata [1248] | 18.2 | $TE_{01}$ | 0.08 | 0.5 | 0.2 | 0.55 | |
| UNIV. Strathclyde | 23 | $TE_{12}$ | 0.1 | 0.5 | 5 | 10 | |
| [1249-1254] | 100 | | 0.2 | 0.22 | 6.3 | 14 | |

r: rectangular waveguide

*) operation from 28 to 49 GHz by magnetically tuning through a family of $TE_{m2}$-modes, with the azimuthal index m ranging from 4 to 10.

Table 20: Present development status of relativistic gyrotron oscillators with MIGs or carbon fiber array cathode.

| Institution u | Frequency [GHz] | Mode | Harmonic No. s | Voltage [MV] | Current [kA] | Power [MW] | Efficiency [%] |
|---|---|---|---|---|---|---|---|
| **IAP, Nizhny Novgorod** | 21.6 | $TE_{11}$ | 1 | 0.3 | 0.03 (3) | 1.5 | 16.7 (0.17) |
| **[485,1173,1255-1263]** | 35.7 | $TE_{21}$ | 2 | 0.3 | 0.03 (3) | 1.5 | 16.7 (0.17) |
| | 49.1 | $TE_{31}$ | 3 | 0.3 | 0.03 (3) | 0.5 | 6.7 (0.07) |
| | 62.4 | $TE_{41}$ | 4 | 0.3 | 0.03 (3) | 0.2 | 2.2 (0.02) |
| | 74.9 | $TE_{51}$ | 5 | 0.3 | 0.03 (3) | 0.12 | 1.3 (0.013) |
| | 115.2 | $TE_{32}$ | 3 | 0.25 | 0.008 | 0.1 | 5.0 |
| | 130.3 | $TE_{42}$ | 4 | 0.25 | 0.008 | 0.1 | 5.0 |
| | 223 | $TE_{25}$ | 2 | 0.25 | 0.003 | 0.045 | 6.0 |
| | 369 | $TE_{35}$ | 3 | 0.25 | 0.003 | 0.019 | 2.5 |
| | 371 | $TE_{38}$ | 3 | 0.25 | 0.002 | 0.010 | 2.0 |
| | 414 | $TE_{39}$ | 3 | 0.25 | 0.002 | 0.008 | 1.7 |
| | 469 | $TE_{35}$ | 3 | 0.25 | 0.003 | 0.020 | 2.5 |
| **Nagaoka Univ. Technology [1264]** | 98-144 | $TE_{n1}$ | n | 0.325 | 0.045(7) | 1.3 | 9(0.06) |

Table 21: Relativistic large orbit harmonic pulse gyrotrons with axis-encircling electron beam. The 21.6-74.9 GHz experiments at IAP used an explosive-emission cathode with kicker ($\tau$ = 10 ns) and the 115-469 GHz experiments employed a quasi-Pierce type thermionic electron gun with kicker ($\tau$ = 10 μs, 1 Hz).

# 6 Quasi-Optical Gyrotrons

| Institution | Frequency [GHz] | Mode resonator | Power [kW] | Efficiency [%] | Pulse length [ms] | Type |
|---|---|---|---|---|---|---|
| **ABB, Baden [450,523]** | 92 | $TEM_{00q}$ | 90 | 10 | 10 | |
| **SPC[1)], Lausanne** | 90.8 | $TEM_{00q}$ | 150 | 15 | 5 | grating output |
| **[122,123,450,1265]** | 100 | $TEM_{00q}$ | 90 | 15 | 15 | |
| | 200 ($2\Omega_c$) | $TEM_{00q}$ | 8 | 3.5 | 15 | |
| **IAP, Nizhny Novgorod [1266]** | 100 | $TE_{061}$ | 260 | 6.5 | 0.04 | echelette cavity |
| **MIT, Cambridge [1267-1269]** | 136 | $HE^{O}_{061}$ | 83 | 18 | 0.003 | confocal |
| | 114.3 | $HE^{O}_{051}$ | 75 | 16 | 0.003 | slot-cavity |
| **Moscow-State UNIV.** | 35 | $TEM_{00q}$ | 1 | 15 | CW | |
| **[1270]** | 95 | $TEM_{00q}$ | 1 | 15 | CW | |
| **NRL, Washington D.C.** | 110 | $TEM_{00q}$ | 80 | 8 | 0.013 | |
| **[1001,1271,1272]** | 115 | $TEM_{00q}$ | 600 | 9 | 0.013 | |
| | | | 431 | 12.7 (SDC) | 0.013 | |
| | | | 197 | 16.1 (SDC) | 0.013 | |
| | 120 | $TEM_{00q}$ | 600 | 9 | 0.013 | |
| | | | 200 | 12 | 0.013 | |
| **CANON[2)], Otawara** | 112 | $TEM_{00q}$ | 100 | 12 | 5 | |
| **[694]** | 120 | $TEM_{00}$ | 26 | 10 (DEB) | 3 | |
| **UESTC, Chengdu [1273-1276]** | 205.7-209.0 | $TE_{06}$ | 20 | 11.8 | 0.1 | confocal cavity |
| | 395.35 ($2\Omega_c$) | $HE^{O}_{011,1}$ | 6.44 | 3.4 | 0.1 | confocal cavity |

SDC: Single-stage Depressed Collector

DEB: Dual Electron Beam (1 annular beam, 1 pencil beam), [1)] Swiss Plasma Center, formerly CRPP, [2)] formerly TOSHIBA

Table 22: Present development status of quasi-optical gyrotron oscillators.

# 7 Cyclotron Autoresonance Masers (CARMs)

| Institution | Frequency [GHz] | Mode | Power [MW] | Efficiency [%] | Gain [dB] | B-Field [T] | Voltage [MV] | Current [kA] | Type |
|---|---|---|---|---|---|---|---|---|---|
| IAP | 31.5-34.5 | $TE_{11}^*/TE_{21}$ ($2\Omega_c$) | 3.4 | 17 (0.21) | - | 1.05-1.2 | 0.40 | 0.05 (4) | CARM-BWO |
| IAP | 35.7 | $TE_{51}$ | 30 | 10 | - | 1.12 | 0.4 | 0.6 | oscillator |
| IAP | 36.5 | $TE_{11}$ | 9 | 18 (0.45) | - | 1.15 | 0.4 | 0.6 | oscillator |
| IAP, IHCE | 37.5 | $TE_{11}$ | 10 | 4 | 30 | 0.5 | 0.5 | 0.5 | amplifier |
| IAP, U. Strath., HERC | 37.5 | $TE_{21}$ | 0.2 | 0.5 (0.25) | | | 0.15 | 0.25 (0.5) | superra-diance |
| IAP | 38 | $TE_{11}^*/TE_{21}$ ($2\Omega_c$) | 13 | 26 (0.65) | - | 1.24 | 0.5 | 0.1 (4) | CARM-gyrotron |
| | 40 | $TE_{11}$ | 6 | 22 (0.44) | - | | 0.46 | 0.06 (0.3) | oscillator |
| IAP, IHCE, JINR | 50 | $TE_{11}$ | 30 | 10 | - | 0.7 | 1.0 | 0.3 | oscillator |
| IAP | 66.7 | $TE_{21}$ | 15 | 3 | - | 0.6 | 0.5 | 1.0 | oscillator |
| IAP, IHCE, JINR | 68 | $TE_{11}$ | 50 | 8 | - | 1.0 | 1.2 | 0.5 | oscillator |
| IAP | 69.8 | $TE_{11}$ | 6 | 4 | - | 0.6 | 0.35 | 0.4 | oscillator |
| IAP [1255,1256,1277-1286] | 125 | $TE_{41}$ | 10 | 2 | - | 0.9 | 0.5 | 1.0 | oscillator |
| LLNL Livermore [1287] | 220 | $TE_{11}$ | 50 | 2.5 | - | 3.0 | 2.0 | 1.0 | oscillator |
| MIT Cambridge [472,1288,1289] | 27.8 | $TE_{11}$ | 1.9 | 5.3 | - | 0.6 | 0.45 | 0.080 | oscillator |
| | 30 | $TE_{11}$ | 0.1 | 3 | - | 0.64 | 0.3 | 0.012 | oscillator |
| | 32 | $TE_{11}$ | 0.11 | 2.3 | - | 0.63 | 0.32 | 0.015 | oscillator |
| | 35 | $TE_{11}$ | 12 | 6.3 (0.04) | 30 | 0.7 | 1.5 | 0.13 (20) | amplifier |
| NRL, Washington DC [1290] | 35,70-90 | $TE_{61}$ | 0.02 | 0.002 | - | 1.0 | 0.6 | 0.2 (100) | oscillator |
| UNIV. Michigan [1291,1292] | 15 | $TE_{11}$ | 7 | 1.5 | - | 0.45 | 0.4 | 1.2 | oscillator |
| UNIV. Strathclyde [1293-1295] | 13 | $TE_{11}$ | | | - | 0.3 | 0.4 | 0.04 | oscillator |
| | 14.3 ($2\Omega_c$) | $TE_{21}$ | 0.18 | 4 (0.4) | - | 0.2 | 0.3 | 0.015 (0.15) | oscillator |

* output mode
HERC Moscow, IAP Nizhny Novgorod, IHCE Tomsk, JINR Dubna

Table 23: State-of-the-art of fast-wave CARM experiments (short pulse).

| Institution | Frequency [GHz] | Mode | Power [MW] | Efficiency [%] | Gain [dB] | B-Field [T] | Voltage [MV] | Current [kA] | Type |
|---|---|---|---|---|---|---|---|---|---|
| UNIV. Lomonosov, Moscow [432] | 9.5 | $TM_{01}$ | 35 | 3.5 | - | 1.15 | 0.4 | 2.5 | oscillator corr.waveguide |
| Tomsk Polytechn. Inst. [433] | 25 | | 20 | 0.2 | - | 0.64 | 0.9 | 14 | oscillator diel.waveguide |
| UNIV. Niigata, NIFS, UNIV. Maryland [434] | 19.5 | $TM_{01}$ | 0.2 | 3.8 | - | 0.9 | 0.035 | 0.15 | oscillator corr.waveguide |
| UNIV. Yale, NRL, Washington D.C. [435] | 6.2 | $TE_{01}$ | 0.02 | 10 | 53 | 0.2 | 0.05 | 0.005 | amplifier diel.waveguide |

Table 24: State-of-the-art of slow-wave CARM experiments (short pulse).

# 8 Gyroklystrons, Gyro-TWT's, Gyrotwystrons, Gyro-BWOs and other Gyro-Devices

## Weakly Relativistic Pulse Gyroklystrons

| Institution | Frequency [GHz] | Mode | No. of cavities | Power [kW] | Efficiency [%] | Gain [dB] | BW [%] | Type |
|---|---|---|---|---|---|---|---|---|
| CPI[1)], Palo Alto [20,447] | 10 ($2\Omega_c$) | $TE_{01}$ | 3 | 20 | 8.2 | 10 | 0.2 | |
| | 28 | $TE_{01/02}$ | 2 | 76 | 9 | 30 | 0.2 | |
| | 35 | | | 65 | | 30 | 0.2 | |
| CPI, Litton, NRL, U.M. [422,646,1296-1303] | 93.8 | $TE_{01}$ | 4 | 118 | 29.5 | 24.7 | 0.64 | SN1 |
| | | | 5 | 130 | 33 | 39.5 | 0.75 | SN2 |
| GYCOM-M(TORIY), Moscow [1304,1305] | 35.2 | $TE_{02}$ | 2 | 750 (5av.) | 24 | 20 | 0.6 | max. power |
| | | | 2 | 350 | 32 | 19 | 0.9 | max. efficiency |
| | 35.0 | $TE_{01}$ | 4 | 160 | 48 | 42 | 1.4 | |
| | | | 3 | 250 (1.2av.) | 35 | 40 | 1.4 | |
| IAP Nizhny Novgorod [1306-1321] | 9.25 | $TE_{01}$ | 2 | 4 | 50 | 22 | 1.0 | |
| | | | 3 | 16 | 45 | 22 | 1.0 | |
| | 15.2 | $TE_{01}$ | 3 | 50 | 50 | 30 | 0.5 | |
| | 15.8 | $TE_{02}$ | 3 | 160 | 40 | 30 | 0.5 | max. efficiency |
| | 32.3 ($2\Omega_c$) | $TE_{02}$ | 3 | 300 | 23 | 26 | 0.05 | PM, 360 kg |
| | | | 2 | 220 | 18 | 13 | 0.27 | PM, 360 kg |
| | 34 | $TE_{01}$ | 4 | 280 | 32 | 34 | 0.53 | |
| | 35.12 ($2\Omega_c$) | $TE_{02}$ | 2 | 258 | 18 | 17 | 0.3 | tapered B-field |
| | 35.2 | $TE_{02}$ | 2 | 750 | 24 | 20 | 0.63 | $TE_{01}$ input through |
| | | | | 430 | | | 0.89 | MIG + mode converter |
| | 93.2 | $TE_{01}$ | 4 | 65 | 26 | 35 | 0.3 | max. power |
| | | | 4 | 57 | 34 | 40 | 0.3 | max. efficiency |
| | 93.5 | $TE_{02}$ | 2 | 140 | 18 | 18 | 0.35 | |
| | | | 2 | 220 | 32 | 20 | 0.15 | shaped B |
| | 93.2 | $TE_{02}$ | 3 | 340 | 27 | 23 | 0.41 | shaped B |
| IECAS, Beijing [578,1322-1324] | 35 ($2\Omega_c$) | $TE_{02}$ | 3 | 212 | 16 | 24 | 0.44 | |
| Kwangwoon Univ., Seoul [1325] | 27.85 | $TE_{01}$ | 5 | 150 | 26 | 50 | 0.1 | |
| NRL, Washington D.C. [418-421,447,1001, 1326-1337] | 4.5 | $TE_{10}$ | 3 | 54 | 30 | 30 | 0.4 | |
| | 34.95 | $TE_{01}$ | 2 | 210 | 37 | 24 | 0.35 | |
| | 34.9 | $TE_{01}$ | 3 | 225 | 31 | 30 | 0.82 | |
| | 34.9 | $TE_{01}$ | 4 | 208 | 30 | 53 | 0.5 | |
| | 85 | $TE_{13}$ | 2 | 50 | | 20 | | |
| | 85.5 | $TEM_{00}$ | 2 | 82 | 19 (30SDC) | 18 | | QOGK |
| | 93.4 | $TE_{01}$ | 4 | 60 | 25 | 27 | 0.69 | max. BW |
| | | | | 84 | 34 | 42 | 0.37 | max. power |
| | | | 5 | 72 | 27 | 48 | 0.44 | max. power x BW |
| UESTC, Chengdu [578,1338] | 34.9 ($2\Omega_c$) | $TE_{01}$-$TE_{02}$ | 4 | 250 (5 av.) | 24 | 36 | 0.4 | |

Table 25: Weakly relativistic pulse gyroklystron experimental results.

# Weakly Relativistic CW Gyroklystrons

| Institution | Frequency [GHz] | Mode | No. of cavities | Power [kW] | Efficiency [%] | Gain [dB] | BW [%] | Type |
|---|---|---|---|---|---|---|---|---|
| CPI, Litton, NRL, U.M. [418-422,537,1296-1303] | 93.8<br>94.2 | $TE_{01}$<br>$TE_{01}$ | 4<br>5 | 10.1<br>10.2 | 33.5<br>31 | 32<br>33 | 0.45<br>0.75 | (92 kW, 11% duty)<br>(102 kW,10% duty) |
| IAP N. Novgorod [1308] | 9.17 | $TE_{11}$ | 2 | 0.7 | 70 | 22 | 0.3 | |
| IAP/ISTOK Moscow [1309,1312,1313] | 91.8 | $TE_{01}$ | 4 | 2.5 | 25 | 30 | 0.35 | |

QOGK: Quasi-Optical Gyro-Klystron;
SDC: Single-stage Depressed Collector
[1)] Communications & Power Industries, formerly VARIAN

Table 26: Weakly relativistic CW gyroklystron experimental results.

Relativistic Pulse Gyroklystron

| Institution | Frequency [GHz] | Mode output | No. of cavities | Power [MW] | Efficiency [%] | Gain [dB] | BW [%] | Type |
|---|---|---|---|---|---|---|---|---|
| IAP, Nizhny Novgorod [1339-1350] | 30 | $TE_{53}$ | 2 ($TE_{52}$/$TE_{53}$) | 15 | 40 | 30 | 0.17 | triode gun |
| | | $TE_{52}$ | 3 ($TE_{52}$/$TE_{52}$/$TE_{53}$) | 12 | 30 | 38 | 0.17 | |
| | 35.4 | $TEM_{00}$ | 2 ($TE_{71}$/$TE_{73}$) | 15 | 33 | 30 | 0.14 | |
| UNIV. Maryland [411-415,1351-1364] | 8.57 | $TE_{01}$ | 3 | 75 | 32 | 30 | 0.2 | coaxial |
| | 9.875 | $TE_{01}$ | 2 | 24 | 30 | 33 | 0.2 | |
| | 9.87 | $TE_{01}$ | 3 | 27 | 32 | 36 | 0.2 | max. power |
| | | | 3 | 16 | 37 | 33 | 0.2 | max. efficiency |
| | | | 3 | 20 | 28 | 50 | 0.2 | max. gain |
| | 17.14 ($2\Omega_c$) | $TE_{02}$ | 3 | 27 | 13 | 25 | 0.1 | coaxial |
| | | | 4 | 18.5 | 7.0 | 23.3 | 0.35 | coaxial |
| | 19.76 ($2\Omega_c$) | $TE_{02}$ | 2 | 32 | 29 | 27 | 0.1 | |
| | 29.57 ($3\Omega_c$) | $TE_{03}$ | 2 | 1.8 | 2.0 | 14 | 0.1 | |

Table 27: Relativistic pulse gyroklystron experimental results.

# Weakly Relativistic Gyro-TWTs

| Institution | Frequency [GHz] | Mode | Power [kW] | Efficiency [%] | Gain [dB] | Bandwidth [%] | Type |
|---|---|---|---|---|---|---|---|
| **BVERI, Beijing [578,1365-1374]** | 34.2 | $TE_{01}$ | 290 (5 av.) | 34 | 65 | 8.0 | periodic SiC loading |
| | 48 | $TE_{01}$ | 150 (5 av.) | 35 | 50 | 7.0 | periodic SiC loading |
| | 95 | $TE_{01}$ | 120 | 32 | 39 | 6.3 | periodic SiC loading |
| | 94 | $TE_{02}$ | 110 (60) | 17 | 32 | 5.0 (8.0) | periodic BeO-SiC loading |
| **CPI[1], Palo Alto [20,422-424,447,646,1303, 1375-1380]** | 5.18 | $TE_{11}$ | 120 | 26 | 20 | 7.3 | MIG |
| | 5.2 | $TE_{11}$ | 64 | 14 | 17.5 | 7.3 | Pierce-helix gun |
| | 93.7 | $TE_{11}$ | 28 | 7.8 | 31 | 2 | Pierce-helix gun |
| | 95 | $TE_{01}$ | 1.5 (0.6 av.) | 4.2 | 42 | 7.7 | |
| **E2V, Chelmsford [1381]** | 10 ($2\Omega_c$) | $TE_{-21}/TE_{+11}$ | 180 | | | | gridded gun |
| **IAE-CAEP, Mianyang [1382]** | 7.8 | $TE_{11}$ | 104 | 29.2/41.6 | 32.2 | 5.1 | SDC |
| **IAP, Nizhny Novgorod [1383-1405] Helical Waveguide Gyro-TWTs** | 36.3 ($2\Omega_c$) | $TE_{-21}/TE_{+11}$ | 180 | 27 | 25 | 10 | cusp gun with axis-encircl. beam 3 μs |
| | 34.3 ($2\Omega_c$) | $TE_{-21}/TE_{+11}$ | 120 | 23 | 20 | 6 | longpulse 110 μs |
| | | | 160 (7.7) | 40 (26) SDC | 23 (26) | 7.7 (7.5) | 100 μs pulse (CW) |
| | 96.2 ($2\Omega_c$) | $TE_{-21}/TE_{+11}$ | 3 | 15 (SDC) | 54 | 2.3 | CW, 2-tubes cascade |
| **IECAS, Beijing [578,1406-1408]** | 16.2 | $TE_{11}$ | 130 | 17.8 | 41 | 12.3 | periodic lossy |
| | 34.5 | $TE_{01}$ | 110 | 15.2 | 33 | 5 | periodic lossy |
| **MIT, Cambridge [1409-1427]** | 140 | $HE^{0}_{061}$ (q.o.) | 30 | 12.5 | 29 | 1.6 | at 0.875 kW 400 ps modulation pulse |
| | | | 0.55 | 0.4 | 35 | 0.9 | |
| | 250 | $TE_{03}$-like | 0.045 | 0.4 | 38 | 3.2 | PBG, 260 ps pulses |
| **NRL, Washington D.C. [447,1428-1434]** | 32.5 | $TE_{10}$ | 6.3 | 10 | 16.7 | 33 | 1-stage tapered |
| | 35.5 | $TE_{10}$ | 8 | 16 | 25 | 20 | 2-stage tapered |
| | 32.3 | $TE_{10}$ | 50 | 28 | 25 | 11 | folded waveguide |
| | 34.0(35.6) | $TE_{01}$ ($TE_{11}$) | 137(70) | 17 (17) | 47 (60) | 3.3 (17) | axis-encircling beam 2-stage output |
| **UC Los Angeles/ Davis [1435-1447]** | 9.3 | $TE_{10}$ | 55 | 11 | 27 | 11 | diel. coat. waveguide |
| | 10.4 ($3\Omega_c$) | $TE_{31}$ | 6 | 5 | 11 | 3 | axis-encirl. beam |
| | 15.7 ($2\Omega_c$) | $TE_{21}$ | 207 | 12.9 | 16 | 2.1 | slotted waveguide |
| | 16.2 ($8\Omega_c$) | $TE_{81}$ | 0.5 | 1.3 | 10 | 4.3 | axis-encircling beam |
| | 92 | $TE_{01}$ | 140 | 22 | 60 | 2.2 | heavily loaded + short copper stage |
| **NTHU, Hsinchu [478-480,1448-1454]** | 35.8 | $TE_{11}$ | 27 | 16 | 35 | 7.5 | 2-stage severed |
| | 34.2 | $TE_{11}$ | 62 | 21 | 33 | 12 | 2-stage lossy (short) |
| | 33.6 | $TE_{11}$ | 93 | 26.5 | 70 | 8.6 | 2-stage lossy (long) |
| **UESTC, Chengdu [578,1455-1481]** | 16 | $TE_{11}$ | 200 (20 av.) | 23.8 | 43 | 16.3 | 3-stage lossy (long) |
| | 16 (15.5) | $TE_{11}$ | 450 (30 CW) | 25 (21) | 40 (41) | 12.5 (8.0) | periodic lossy circuit |
| | 16 | $TE_{01}$ | 420 | 23 | 35 | 10 | periodic lossy circuit |
| | 20.8 | $TE_{01}$ | 155.3 (15.5 av.) | 33.8 (SDC) | 50 | 13.5 | lossy + SDC |
| | 29.7 | $TE_{01}$ | 388 (46.6 av.) | 26.9 | 52 | 9.4 | lossy + cutoff section |
| | 29.7 | $TE_{01}$ | 137-160 | 22.3 | 40 | 13.5 | curved profile circuit |
| | 34 | $TE_{01}$ | 169 (20.3 av.) | 29.4 | 50.2 | 5.5 | periodic lossy circuit |
| | 47 | $TE_{01}$ | 208(111, 50 av) | 22.2 (18.8) | 65 | 8.8 | lossy circuit |
| | 94 | $TE_{01}$ | 126.1 (20.2 av) | 32.3 | 43 | 10 | lossy circuit |
| **UNIV. Kwangwoon [1482]** | 14.4 | $TE_{10}$ | 14.9 | 18 | 27 | 7 | two-stage circuit |
| **UNIV. Strathclyde [1483-1491]** | 93 ($2\Omega_c$) | $TE_{-21}/TE_{+11}$ | 3.4 | 4.2 | 37 | 5.8 | cusp gun with axis-encircling beam |
| **UNIV. Tel Aviv [1492]** | 7.3 | $TE_{10}$ | 0.8 | 12 | 26 | | 3-stage output |

[1] Communications & Power Industries, formerly VARIAN

Table 28: Present development status of weakly relativistic gyro-TWTs (short pulse and CW operation (IAP)).

# Relativistic Gyro-TWTs

| Institution | Frequency [GHz] | Mode | Power [MW] | Efficiency [%] | Gain [dB] | Bandwidth [%] | Type |
|---|---|---|---|---|---|---|---|
| **IAP, Nizhny Novgorod UNIV. Strathclyde [481-483,1383-1385, 1493-1497]** | 9.4 ($2\Omega_c$) | $TE_{-21}/TE_{+11}$ | 1.1 | 29 | 37 | 21 | helical waveguide with $\Delta m=3$ perturb. axis encircling e-beam |
| | 36.5 ($2\Omega_c$) | $TE_{-21}/TE_{+11}$ | 3.0 | 27 | 33 | 20($\Delta B$) | see above |
| **MIT, Cambridge [1498]** | 17.1 ($2\Omega_c$) | $TE_{21}$ | 2 | 4 | 40 | | Pierce-helix gun |
| | 17.1 ($3\Omega_c$) | $TE_{31}$ | 4 | 6.6 | 51 | | Pierce-helix gun |
| **NRL, Washington D.C. *) [1499,1500]** | 35 | $TE_{11}$ | 20 | 11 | 30 | | explosive-emission gun, bifilar helical wiggler |
| **UNIV. Strathclyde [1501-1506]** | 9.4 ($2\Omega_c$) | $TE_{-21}/TE_{+11}$ | 0.22 | 20 | 24 | 21 | thermionic MIG, superradiance |
| | | | 1.3 | 27 | 47 | 3 | cold cathode cusp gun |

*) This gyro-TWT operated near the "grazing intersection" in the dispersion diagram could also have been considered a CARM amplifier with frequency 4.4 times the relativistic cyclotron frequency.

Table 29: Present development status of relativistic gyro-TWTs (short pulse).

# Weakly Relativistic Pulse Gyrotwystrons

| Institution | Frequency [GHz] | Mode | | Power [kW] | Efficiency [%] | Gain [dB] | BW [%] |
|---|---|---|---|---|---|---|---|
| | | cavity | TW section | | | | |
| **CPI[1], Palo Alto [422,424,537,1303]** | 94 | $TE_{01}$ (4 cav.) | $TE_{01}$ | 59 (5.9 av.) | 14.9 | 35 | 1.6 |
| **NRL, Washington D.C. [1507,1508]** | 4.5<br>31.5<br>93.5 | $TE_{10}$<br>$TE_{42}$ ($2\Omega_c$)<br>$TE_{01}$ (3 cav.) | $TE_{10}$<br>$TE_{42}$<br>$TE_{01}$ | 73<br>160<br>48 | 22.5<br>25<br>17.5 | 37<br>30<br>30 | 1.5<br>1.3<br>2.0 |
| **IAP, N.Novgorod, NRL Washington D.C. [1509,1510]** | 9.2 | $TE_{01}$ (2 cav.) | $TE_{01}$ | 4.8<br>4.4 | 14<br>27.5 | 20<br>18 | 0.9<br>1.6 |

[1] Communications & Power Industries, formerly VARIAN

Table 30: State-of-the-art of weakly relativistic gyrotwystron experiments (short pulse).

# Weakly Relativistic Pulse Harmonic-Multiplying Inverted Gyrotwystrons/Gyro-TWT/Gyrotriotron

| Institution | Frequency [GHz] | Mode cavity | Mode TW section | Power [kW] | Efficiency [%] | Gain [dB] | BW [%] |
|---|---|---|---|---|---|---|---|
| IECAS [1511-1518] | 33.1 | $TE_{01}$/coupled cavity ($2\Omega_c$) $TE_{02}/TE_{03}$ | $TE_{03}$ ($\Omega_c$) | 75 | 7.1 | 25 | 1.1 |
| Seoul National UNIV. [1519] | 33.9 | $TE_{10}$ | $TE_{10}$ ($3\Omega_c$) | $10^{-4}$ | $2 \cdot 10^{-3}$ | LO-gyro-TWT | 3.8 |
| UNIV. Maryland. [484,1520-1525] | 31.8 | $TE_{22}$ | $TE_{42}$ ($2\Omega_c$) | 100 | 20 | 30 | 1.3 |
| | 33.7 | $TE_{02}$ | $TE_{03}$ ($2\Omega_c$) | 430 | 35 | 30 | 0.3 |
| | 34.6 | $TE_{02}$ | $TE_{03}$ ($2\Omega_c$) | 180 | 32 | 30 phase-locked oscillator | 3.0 |
| | 32.5 | $TE_{02}$ | $TE_{03}$ ($2\Omega_c$) | 200 | 12 | 36 gyro-TWT | 3.0 |
| | 35 | $TE_{02}/TE_{03}$ ($2\Omega_c$) | $TE_{04}$ ($2\Omega_c$) | 110 | 32 | 53 gyro-TWT | 3.0 |
| | 33.75 | Gyrotriotron | | 126 | 12 | 27 | 3.2 |
| | TWT input stage ($s_1$=1) $TE_{02}$ / 4-unit clustered cavities ($s_2$=2) $TE_{03}$ / TWT output stage ($s_3$ = 2) $TE_{04}$ | | | | | | |

Table 31: State-of-the-art of weakly relativistic harmonic gyro-devices (short pulse).

# Relativistic Pulse Gyrotwystrons

| Institution | Frequency [GHz] | Mode cavity | Mode TW section | Power [MW] | Efficiency [%] | Gain [dB] | BW [%] |
|---|---|---|---|---|---|---|---|
| UNIV. Maryland [1364,1526] | 9.878 | $TE_{01}$ | $TE_{01}$ | 21.6 | 21 | 25.5 | |
| | 19.76 | $TE_{01}$ (9.88GHz) | $TE_{02}$ ($2\Omega_c$) | 12 | 11 | 21 | |

Table 32: State-of-the-art of relativistic gyrotwystron experiments (short pulse).

# Weakly Relativistic Pulse Gyro-BWOs

| 1420-1423 | Frequency [GHz] | Mode | Power [kW] | Efficiency [%] | Bandwidth [%] | Type |
|---|---|---|---|---|---|---|
| **UNIV. Strathclyde IAP N. Novgorod [1527-1530]** | 8.6 ($2\Omega_c$) | $TE_{+21}/TE_{-11}$ | 65 | 16.5 | 17 | quasi-Pierce gun with kicker |
| **IAP, N. Novgorod KIT[1)], Karlsruhe [382,1190,1386-1392, 1531,1532]** | 24.7 ($2\Omega_c$) | $TE_{+21}/TE_{-11}$ | 7 | 15<br>23 (SDC) | 5 | MIG CW operation |
| **IAP, Nizhny Novgorod [1389,1401]** | 35-38 ($2\Omega_c$)<br>35 ($2\Omega_c$)<br>96 ($2\Omega_c$) | $TE_{+21}/TE_{-11}$<br>$TE_{+21}/TE_{-11}$<br>$TE_{+21}/TE_{-11}$ | 34<br>10<br>1.3 | 7<br>7 | 15<br>15<br>4.2 | quasi-Pierce gun with kicker<br>cusp gun with thermal cathode<br>cusp gun with thermal cathode two-tubes cascade |
| **IECAS, BVERI, Beijing [1533,1534]** | 17.2 | $TE_{01}$ | 48 | 10.5<br>21 (SDC) | 5 | $TE_{10}^r$ output |
| **MIT, Cambridge, LLNL, Livermore [1535]** | 140 | $TE_{12}^c$ | 2 | 2 | 9 | |
| **NRL, Washington D.C. [1536]** | 27.8<br>29.2 | $TE_{10}^r$<br>$TE_{10}^r$ | 2<br>6 | 9<br>15 | 3<br>13 | electric tuning<br>magnetic tuning |
| **NTHU, Hsinchu [1537-1545]** | k33.5 | $TE_{11}^c$<br><br><br><br><br>$TE_{01}^c$<br>$TE_{02}^c$ | 20-67<br>115<br>149<br>154<br>164<br>123<br>2.8 | 6.5-21.7<br>23<br>30<br>39<br>41<br>24.5<br>22.6 | 5<br>8.5<br>4<br>1<br>1<br>15.8<br>9.5 | injection locked<br>free running<br>electric + magnetic tuning<br>injection locked<br>inverse injec. locked<br>sliced circuit<br>sliced circuit |
| **UNIV. Strathclyde [1546-1551]** | 95 ($2\Omega_c$) | $TE_{+21}/TE_{-11}$ | 12 | 20 | 15.3 | magnetic tuning, casp gun |
| **UNIV. Utah [1552]** | 10 | $TE_{10}^r$ | 0.72 | 10 | 8 | |

r = rectangular waveguide; c = circular waveguide, [1)]formerly KfK, then FZK

Table 33: Experimental results on weakly relativistic pulse gyro-BWOs (short pulse and CW operation (IAP)).

# Relativistic Pulse Gyro-BWOs

| Institution | Frequency [GHz] | Mode | Power [MW] | Efficiency [%] | BW [%] | Voltage [MV] | Current [kA] | Type |
|---|---|---|---|---|---|---|---|---|
| **IAP, N. Novgorod [1553,1554]** | 10<br>35($2\Omega$c) | $TM_{11}$<br>$TE_{-21}/ TE_{+11}$ | 200<br>1.15 | 22<br>10 axis | <br>15 ($\Delta$B) encircling | 0.45<br>0.35 e-beam | 2<br>0.032 | Cherenkov with cycl. mode selection<br>helical w.g. with $\Delta$m=3 perturbation |
| **UNIV. Kanazawa [1555,1556]** | 9-13 | $TE_{10}^r$ | 1 | 0.75 (0.02) | 1 | 0.45 | 0.3(10) | |
| **UNIV. Michigan [1557,1558]** | 4-6<br>5-6 ($2\Omega$c) | $TE_{11}$<br>$TE_{11}$ | 55 (30)<br>1 | 8 (4.3)<br>0.15 | 1<br>4 | 0.7 | 1 | |
| **USAF Phillips Lab. Aberdeen [1559,1560]** | 4.2<br>4.4 | $TE_{21}$<br>$TE_{01}$ | 4<br>0.15 | 1<br>0.04 | 1<br>1 | 0.4<br>0.4 | 1<br>1 | |

r = rectangular waveguide

Table 34: Experimental results on relativistic gyro-BWOs (short pulse: 0.01 – 1 μs).

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