



KIT SCIENTIFIC REPORTS 7765

State-of-the-Art of High-Power Gyro-Devices

Update of Experimental Results 2023

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by
Manfred Thumm

Institut für Hochleistungsimpuls- und Mikrowellentechnik (IHM)

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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, $P_{\text{out}} = 4\text{-}50$ kW, CW, $\eta \geq 30\%$. Gyrotrons with pulsed magnet for various short-pulse applications deliver $P_{\text{out}} = 210$ kW with $\tau = 20$ μs at frequencies up to 670 GHz ($\eta \cong 20\%$), $P_{\text{out}} = 5.3$ kW at 1 THz ($\eta = 6.1\%$), and $P_{\text{out}} = 0.5$ 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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Please send corrections, completions and supplements to manfred.thumm@kit.edu

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, zweiseitigem 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. Gyrotron-oszillatoren (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, $P_{\text{out}} = 4-50$ kW, CW, $\eta \geq 30\%$. Gyrotrons mit gepulstem Magnet für verschiedene Kurzpuls-Anwendungen arbeiten bei Frequenzen bis zu 670 GHz bei $P_{\text{out}} = 210$ kW und $\tau = 20$ μs ($\eta \cong 4\%$), $P_{\text{out}} = 5,3$ kW bei 1 THz ($\eta = 6,1\%$) und $P_{\text{out}} = 0,5$ 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 $B_0=1-3.6$ Tesla. As fusion machines become larger and operate at higher magnetic field ($B_0 \cong 5.5$ 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, $\tau = 0.2 \mu s$ 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 HE₁₁ 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].

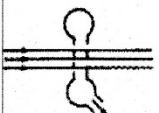
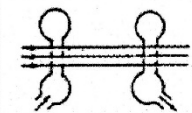
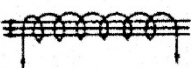
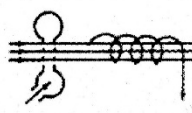
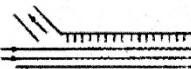
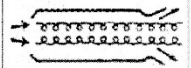
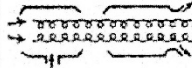
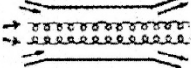
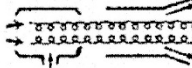
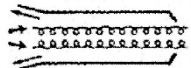
"O" TYPE DEVICES	 MONOTRON	 KLYSTRON	 TWT	 TWYSTRON	 BWO
TYPE OF GYRO-DEVICE	 GYRO-MONOTRON	 GYRO-KLYSTRON	 GYRO-TWT	 GYRO-TWYSTRON	 GYRO BWO

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		Power [MW]	Efficiency [%]	Pulse length [s]
		cavity	Output			
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 (2Ω _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 (2Ω _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 _{6,2} /TE _{15,1}	TEM ₀₀ /TE _{15,1}	0.5/1.25	35	0.1/0.0001
	53.2,54.5	TE _{8,3}	TEM ₀₀	0.5 (0.3)	40 (36)	0.1 (1.0)
	53.5 (3Ω _c)	TE _{7,1/7,2}	TE _{7,2}	0.15	10	0.00004
	68 (70)	TE _{9,3}	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
	64-91	low-Q cavity tunable echelette	Mode	80-200	11-30	0.0001
	HUGHES, Torrance [447]	60	TE ₀₂	TE ₀₂	0.2	35
IECAS, Beijing [574-578]	24.1	TE ₀₁	TE ₀₁	0.15	24	0.02
	34.3(2Ω _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 _{8,3} /TE _{8,3}	TEM ₀₀	0.055/0.4/0.2	46/50/38 (SDC)	30/5.0/3.0
	95	TE ₀₃ /TE _{6,2}	TE ₀₃ /TEM ₀₀	0.02/0.03/12	20	10/600/CW
	94(2Ω _c)/95(3Ω _c)	TE ₀₂ /TE _{6,1}	TEM ₁₁ /TE _{6,1}	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 (3Ω _c)	TE ₅₁ /TE ₅₂	TE ₅₂	0.147	10.2	0.0001PM, 100kg
	70,94 (2Ω _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		Power [MW]	Efficiency [%]	Pulse length [s]
		cavity	output			
CPI ¹⁾ , Palo Alto [15,56,283,533-537,546-549,633-658]	106.4(2Ω _c)	TE _{02,03}	TE ₀₃	0.135	21	0.1
	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 [127-139,659-678]	117.9	TE _{19,5}	TEM ₀₀	1.55	31	0.007
				1.55	49.5 (SDC)	0.007
	132.6	TE _{9,4}	TE _{9,4}	0.42	21	0.005
GYCOM-M, IAP Moscow, N. Novgorod [16,452,562,679-688]	110	TE _{19,5}	TEM ₀₀	1.2	40	0.0001
				1.0	65(SDC)	0.0001
				0.93	36	2.0
				0.5	35	5.0
				0.35	33	10.0
GYCOM, IAP Nizhny Novgorod [16,125,126,140-159,558-563, 689-693]	100	TE _{22,2}	TE _{22,2}	1.1	34	0.0001
	104	TE _{18,7}	TEM ₀₀	0.98	46.5 (SDC)	0.5
	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⁾ Naka, Otawara [23,620-622,694-722]	104.1	TE _{19,7}	TEM ₀₀	0.9	41 (SDC)	300
	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 [723,724]	120	TE _{02,03}	TE ₀₃	0.16	25	0.06
	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⁾ , Vélizy [450,607]	100	TE ₃₄	TE ₃₄	0.19	30	0.07
	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 ($100 \text{ GHz} \leq f < 140 \text{ GHz}$, $\tau \geq 0.1 \text{ ms}$).

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 [15,20,283,533-537,546,548,549, 642-646,649-653,655-657,739-744]	140	TE _{02/03}	TE ₀₃	0.1	27	CW	
	140	TE _{15,2}	TE _{15,2}	1.04(0.32)	38 (31)	0.0005(3.6)	
	140.2	TE _{28,7}	TEM ₀₀	0.2 (0.4)	31	avg. (peak)	
	170	TE _{31,8}	TEM ₀₀	0.92/0.9	36/33 (SDC)	0.003/1800	
				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 [127-139,451,659-678,748-764]	140.2	TE _{10,4}	TE _{10,4}	0.69	28	0.005	
	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⁾ , [6,7,70-82,95-104,728,765-809] EGYC ⁶⁾ [810-824]	139.8	TE _{28,8}	TEM ₀₀	1.0/0.92	50/44 (SDC)	12/1800	
	140.3	TE _{28,10}	TEM ₀₀	1.7/1.5	43/45 (SDC)	0.001	
	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 Nizhny Novgorod [16,140-159,483,559-563,681-688, 693,825-803]	140	TE _{22,6}	TEM ₀₀	0.96	36	1.2	
				0.54	36	3.0	
				0.26 (0.1)	36	10 (80)	
			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 Nizhny Novgorod [16,125,126,558-560,563,567, 686-689,691,692,825,840,864-870]	140	TE _{22,6}	TEM ₀₀	0.8	32	0.8	
				0.88	50.5 (SDC)	1.0	
				0.55	33	2.0	
	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⁾ Naka, Otawara [23,700-715,871-917]	170	TE _{22,6}	TEM ₀₀	0.45	19	0.05	
				0.25	32 (SDC)	0.4	
	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⁾ Toki, Ibaraki, Otawara [87-90,554,616,618-622,922-924]	154	TE _{28,8}	TEM ₀₀	1.25	37 (SDC)	0.004	
				0.35	39 (SDC)	1800	
	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 ($f \geq 140$ GHz, $\tau \geq 0.1$ ms).

Institution	Frequency [GHz]	Mode		Power [MW]	Efficiency [%]	Corrug.Cavity	
		cavity	output			inner	outer
KIT ¹⁾ Karlsruhe [6,23,26-29,98-100,759-765, 781,925-944] Pulse length ≤ 10 ms	137.78	TE _{27,16}	TE _{27,16}	1.03	24.3	yes	no
	139.96	TE _{28,16}	TE _{28,16}	1.17	27.2	yes	no*
			TE _{76,2} /TEM ₀₀	0.95	20	yes	no
				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] Pulse length ≤ 100 ms	170	TE _{34,19}	TEM ₀₀	2.1(1ms)	48 (SDC)	yes	no
				2.1/1.5 (11/35ms)	47/42 (SDC)	yes	no
IAP, Nizhny Novgorod [14,16,559,562,983-991] Pulse length ≤ 0.1 ms	45	TE _{15,1}	TE _{15,1}	1.25	43	no	no
	100	TE _{21,18}	TE _{21,18}	1.0	35	yes	no
				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 Ω_c)	TE _{33,8}	TE _{33,8}	0.1	11	yes	no	
IAP, KIT ¹⁾ Karlsruhe [925] Pulse length 30 μ s	133	TE _{27,15}	TE _{27,15}	1.3	29	no	no
	140	TE _{28,16}	TE _{28,16}	1.0	23	no	no
MIT, Cambridge [992-995] Pulse length 3 μ s	137	TE _{25,11}	TEM ₀₀	0.5	7.5	no	no
	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 Ω_c)	TE ₀₂ /TE ₀₄	TEM ₀₀	0.02	5	no	no
	two electron beams						

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 μ s – 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		Power [MW]	Efficiency [%]	Pulse length [s]
		cavity	output			
CPI ¹⁾ , Palo Alto [27,30,532-550,637-646,649-658, 739-744]	8	TE ₂₁	TE ₁₀	0.4	26.6	0.0005
	(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
	140.2	TE _{27,8}	TEM ₀₀	0.52 0.92/0.9	29 (SDC) 36/33 (SDC)	10 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 Palo Alto, Toki [87-90,538]	84	TE _{15,3}	TEM ₀₀	0.5	29	2.0
				0.59	41 (SDC)	0.001
				0.25	32 (SDC)	0.2
KIT ²⁾ , Karlsruhe [24,127-134,659-678,754-765]	117.9	TE _{19,5}	TEM ₀₀	1.55	49.5 (SDC)	0.007
	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⁾ , [7,27,30,71-75,98-113,728,765-824]	139.8	TE _{28,8}	TEM ₀₀	1.0/0.92	50/44 (SDC)	12/1800
	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 Nizhny Novgorod [560-562,565-568,573,682,683,688,690]	68 (70)	TE _{9,3}	TEM ₀₀	0.5 (0.68)	50 (48) (SDC)	1.0 (3.0)
	75	TE _{11,5}	TEM ₀₀	0.8	70 (SDC)	0.1
	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
GYCOM, IAP Nizhny Novgorod [27,30,140-159,567,829-861,864]	140	TE _{22,8}	TEM ₀₀	1.7 1.14/0.95/0.7	42 59/52/49 (SDC)	0.0001 10/300/1000
	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. [1001]	115	QOG	TEM ₀₀	0.43	12.7 (SDC)	10 ⁻⁵
				0.20	16.1 (SDC)	10 ⁻⁵
QST ⁵⁾ , CANON ⁶⁾ Naka, Otawara [27,30,697-722,871-917,920,921]	104.1	TE _{19,7}	TEM ₀₀	0.9	41 (SDC)	300
	110	TE _{22,2}	TEM ₀₀	0.61/0.35	50/48 (SDC)	0.05/5.0
	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
	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
NIFS, TSUKUBA UNIV., CANON ⁶⁾ Toki, Ibaraki, Otawara [27,30,87-92,554,611-622,921-924]	77	TE _{18,6}	TEM ₀₀	1.9 1.8/1.6/1.2/0.22	38 (SDC) 38 (SDC)	0.1 0.1/1.8/10/4500
	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) ($\tau \geq 10 \mu\text{s}$).

Institution	Frequency [GHz]	Mode		Power [MW]	Efficiency [%]	Pulse length [s]	
		cavity	output				
KIT ¹⁾ , Karlsruhe [27-30,127-139,664,667, 669-678]	114.2	TE _{18,5}	TEM ₀₀	0.85	23	0.001	optimized
	117.9	TE _{19,5}	TEM ₀₀	1.0	27	0.001	
	121.6(119.5)	TE _{20,5} (TE _{19,7})	TEM ₀₀	1.0(0.88)	49.5 (SDC) 27(23)	0.007 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	
	143.7(143.4)	TE _{23,6} (TE _{23,8})	TEM ₀₀	1.1(1.2)	60 (SDC) 30(40.7)	0.007 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	
	166.0(165.9) (169.2)	TE _{26,7} (TE _{27,9}) (TE _{28,9})	TEM ₀₀ TEM ₀₀	1.0(1.1) (1.15)	50 (SDC) 26(31.9) (35.7)	0.007 0.001 0.001	
GYCOM, IAP Nizhny Novgorod [27-30,125,126,140-159, 562,564-567,688,1002]	71.5	TE _{10,5}	TEM ₀₀	0.8	56	0.15	.
	74.8	TE _{11,5}	TEM ₀₀	0.8	56	0.15	
	78.1	TE _{12,5}	TEM ₀₀	0.8	56	0.15	
	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⁾ Naka, Otawara [27,30,892,1004]	166.7	TE _{30,8}	TEM ₀₀	0.54	27	0.001	plane window
	170	TE _{31,8}	TEM ₀₀	0.62	32	0.001	plane window
QST ²⁾ , TSUKUBA, CANON ³⁾ Naka, Ibaraki, Otawara [30,919,920]	225.96	TE _{26,13}	TE _{26,13}	0.274	18.1	0.002	plane window
	228.13	TE _{24,14}	TE _{24,14}	0.285	18.8	0.002	plane window
	242.1	TE _{25,15}	TE _{25,15}	0.288	18.9	0.002	plane window
	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 [1005-1014]	107.1	TE _{21,6}	TEM ₀₀	1.1	30	0.000003	plane window
	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 TE_{22,10}-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 μ s 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		Power [MW]	Efficiency [%]	Pulse length [s]	No. of Frequencies
		cavity	output				
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 Nizhny Novgorod [27-30,40-55,142-159,563, 567,688, 691-693,841-861, 1002,1017]	121.5	TE _{20,5}	TEM ₀₀	0.5	30	0.1	3F-Gyrotron
	140.0	TE _{22,6}	TEM ₀₀	0.5	30	0.5	3F-Gyrotron
	158.5	TE _{24,7}	TEM ₀₀	0.5	30	0.7	3F-Gyrotron
	105.1	TE _{17,6}	TEM ₀₀	1.04/0.85	59/50 (SDC)	10/300	2F-Gyrotron
	140.1	TE _{22,8}	TEM ₀₀	1.14/0.95	57/52 (SDC)	10/300	2F-Gyrotron
	134.7	TE _{20,8}	TEM ₀₀	0.78	42.2 (SDC)	0.1	2F-Gyrotron
IAE-CAEP, Mianyang [1018-1020]	105.1	TE _{18,7}	TEM ₀₀	0.71	34.0 (SDC)	0.001	2F-Gyrotron
	139.4	TE _{24,9}	TEM ₀₀	1.06	49.0 (SDC)	0.001	2F-Gyrotron
QST ⁵⁾ , CANON ⁶⁾ Naka, Otawara [27,30,892,895,897-912, 915,917,1004,1021-1023]	104.1	TE _{19,7}	TEM ₀₀	0.9	41 (SDC)	300	4F-Gyrotron
	136.8	TE _{25,9}	TEM ₀₀	1.0/	44 (SDC)	300	4F-Gyrotron
	170	TE _{31,11}	TEM ₀₀	1.2/1.0/0.6	47/46/46 SDC	5/300/2000	4F-Gyrotron
	203	TE _{37,13}	TEM ₀₀	1.0/0.6	50 (SDC)	3/10	4F-Gyrotron
QST ⁵⁾ , CANON ⁶⁾ Naka, Otawara [622,716-722]	82	TE _{17,6}	TEM ₀₀	1.0/0.4	35 (SDC)	1/2	3F-Gyrotron
	110	TE _{22,8}	TEM ₀₀	1.9/1.5/1.0	47/45 (SDC)	1/5.0/100	3F-Gyrotron
	137.6	TE _{27,10}	TEM ₀₀	1.9/1.3/1.0	43 (SDC)	1/1.3/100	3F-Gyrotron
NIFS, TSUKUBA UNIV., CANON ⁶⁾ Toki, Ibaraki, Otawara [620,621,722,920- 923,1024]	28.04	TE _{8,5}	TEM ₀₀	1.65	31	0.002	2F-Gyrotron
	34.83	TE _{10,6}	TEM ₀₀	1.21	27	0.002	2F-Gyrotron
	115.5	TE _{21,7}	TEM ₀₀				2F-Gyrotron
	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 (JASTECH) 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		Power [MW]	Efficiency [%]	Pulse length [s]
		cavity	output			
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 ≈ 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 wa- ter 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 (**) HE₁₁ 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 p.c.	BN (CVD) p.c.	Si ₃ N ₄ composite (SN-287)	Sapphire (Al ₂ O ₃) s.c. orientation of E c ⊥ \vec{E}	Silicon Au-doped s.c.	Diamond (PACVD) p.c.	Si C (6 H) p.c.
Thermal Conductivity 300 K k [W/mK] 500 K	260	55	59	40 6	150	2000 1100	330
Ultimate Bending Strength σ_B [MPa]	140	80	800	410	1000	Growth 450 Nucleation 800	440
Poissons Number ν	0.3	0.25	0.28	0.22	0.1	0.1	0.18
Density ρ [g/cm ³]	2.85	2.3	3.4	4.0	2.3	3.515	3.2
Specific Heat Capacity c_p [J/g K]	1.05	0.8	0.6	0.8	0.7	0.502	0.38
Young's Modulus E [GPa]	345	70	320	385	190	1050	700
Therm. Expans. Coeff. α [10 ⁻⁶ /K]	7.2	3	2.4	5.5	2.5	1.0	4.3
Permittivity (145 GHz) ϵ_r'	6.7	4.7	7.84	9.4	11.7	5.67	9.92
Loss Tangent (145 GHz) $\tan\delta$ [10 ⁻⁵]	70	115	30	20	0.35	2	7
Metallizing and Brazing Bakeout Temperature	o.k.	o.k.	o.k. 550°C	o.k. 550°C	o.k. 550°C	o.k. 450°C	o.k. 550°C
Possible Size \varnothing [mm]	150	145	300	270	127	120	
Cost	medium	medium	high	high	low	very high	medium
Failure Resistance R' [W/mm ²] R' = $k\sigma_B(1-\nu)/E\alpha$	10.3	15.7	44.5	6.0	284	772	40
RF-Power Capacity P _T [100W ² /mm ⁴ K] P _T = R'ρ c _p /((1+ε _r ')tanδ)	0.06	0.05	0.36	0.09	106	106	0.63
Radiation Sensitivity n(10 ²⁰ -10 ²¹ n/m ²) γ/X (0.75 Gy/s)				no no	no no	no 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 ₂ O 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 σ_B [MPa]	410	1000	450
Poissons Number ν	0.22	0.1	0.1
Density ρ [g/cm ³]	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. α [10 ⁻⁶ /K]	5.5	2.5	1.2
Permittivity (145 GHz) ϵ_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 \varnothing [mm]	270	127	160
Cost	high	low	very high
Failure Resistance R' [W/mm ²] $R' = k\sigma_B(1-\nu)/E\alpha$	130 (2871)	2463	3214
RF-Power Capacity P _T [100W ² /mm ⁴ K] $P_T = R'\rho c_p / ((1+\epsilon_r')\tan\delta)$	71 (4460)	907	441
Radiation Sensitivity $n(0.3 \cdot 10^{21} \text{ n/m}^2)$ 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) $\tan\delta = 2.5 \cdot 10^{-4}$, $k = 40$ W/mK
②	Diamond	single-disk	Gaussian	circular ($\varnothing = 80$ 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 ($\varnothing = 80$ 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 ($\varnothing = 80$ 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 ($\varnothing = 80$ 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 HE₁₁-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 _{13,2} / TE _{12,3}	7/22	2/3.5	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 IAP, Nizhny Novgorod [1118-1121]	84.9	TE ₃₁	3	2.5	6.3	1
	89.3	TE ₃₁	3	1.7	3.3	1
	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
			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, Nizhny Novgorod [188-194,196-204,338,363,364,1135-1138]	250	TE _{20,2}	0.3	31	30 - 80	pulsed magnetic field
	304	TE _{22,8}	0.3	25	25	
	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	CW operation
	263.2	TE _{5,3}	0.001	17	CW	
MIT, Cambridge [124,993,1005-1014,1139-1154]	107.1	TE _{21,6}	0.94	24	3	output mode parity 96% PBG resonator, BW = 35%
	110	TE _{22,6}	1.67	42	3	
		TEM ₀₀	1.5	48 (SDC)	3	
	113.2	TE _{23,6}	1.18	30	3	
	140	TE _{04-like}	0.025	7.4	3	
	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	slotted cavity/ 0.1 W with cold cathode
	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	
	228.6	TE ₅₂	0.025	14.9	4	
UNIVERSITY, Fukui [27,223,226-241,1104-1107,1159]	202.9	TE ₃₃	0.001	10	10000	TEM ₀₀ output mode
	278	TE ₃₃	0.001	5	1000	
	290	TE ₆₂	0.001	4	1000	
	294	TE _{14,2}	0.246	27	40	
	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 TE₀₁ mode near the fundamental cyclotron frequency at 95 GHz, the output cavity oscillated at the 3rd harmonic 285 GHz in the TE₀₃-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 TE₃₅-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 μ s).

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 μ s).

4 Gyrotrons for Technological Applications

Institution	Frequency [GHz]	Mode		Power [kW]	Efficiency [%]	Voltage [kV]	Magnet
		cavity	output				
CPI ¹⁾ , Palo Alto [15,20,1085]	28	TE ₀₂	TE ₀₂	15	38	40	room temp.
	28 (2Ω _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 (2Ω _c)	TE ₁₁	TE ₁₁	3.5	23	12	room temp.
	24.1 (2Ω _c)	TE ₂₁	TE ₁₁	3.4	23	15	PM, 116kg
	24.1	TE ₃₂	TE ₃₂	36	50	33	room temp.
	24.1 (2Ω _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 (2Ω _c)	TE ₀₂	TE ₀₂	10	42	26	room temp.
				30	35	26	room temp.
	28.1/28.7 (2Ω _c)	TE ₀₃ /TE ₂₃	TE ₀₃ /TE ₂₃	10	20	23-24	2 kHz frequency switching PM, 68 kg ²⁾
	28.25 (2Ω _c)	TE ₁₂	TE ₁₂	12	20	25	
	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 (3Ω _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 (2Ω _c)	TE ₀₃	TE ₀₃	2.4	9.5	18	cryo. mag.	
191.5 (2Ω _c)			0.55	6.2	22	cryo. mag.	
250 (2Ω _c)	TE ₀₂	TE ₀₂	4.3	18	20	cryo. mag.	
250 (2Ω _c)	TE ₆₅	TE ₆₅	1	5	20	cryo. mag.	
326 (2Ω _c)	TE ₂₃	TE ₂₃	1.5	6	20	cryo. mag.	
KIT, Karlsruhe [1202]	28 (2Ω _c)	TE ₁₂	TE ₁₂	22.5	43	23.4	room temp.
MICRAMICS, San Jose [1203]	24.1 (2Ω _c)	TE ₂₂	TEM _{mixed}	5	25	23	room temp.
			TE ₂₂	10	25	23	room temp.
MITSUBISHI, Amagasaki [404,1204-1206]	28 (2Ω _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 [1216-1230]	9.23	TE ₀₁	0.27 (0.28)	0.12 (0.06/0.045)	10 (8/7)	30 (45/50)	explos. cath.+ kicker injection locking slotted echelette cavity, n = 3-10 TEM ₀₀ output and counter rotating input for injection locking
	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	
		TE _{7,3}					
	53.5 (2Ω _c)	TE _{1,5}	0.260	0.013	1.2	35	
	55.0 (2Ω _c)	TE _{6,3}	0.242	0.014	1.3	38	
	55.7 (2Ω _c)	TE _{11,2}	0.22	0.0325	2	28	
	79-107	TM _{1n}	0.5	2-6.5	30	3-1	
94.4	TE _{12,5}	0.24	0.103	5.6	23		
IAP, Nizhny Novgorod Lebedev/General Phys. Inst. Moscow [1218,1231-1233]	10	TE ₁₃	0.3	0.4	25	20	slotted cavity
	10	TE ₁₃	0.3	1.0	60	15	plasma-filled slotted cavity
	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 [1235-1241]	2.88	TE ₀₁ ^r	0.8	2 (7)	20	1.3 (0.4)	small orbit
			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
10	TE ₁₁	0.4	0.025	20		non-slott. coax. cavity	
NRL, Washington D.C. [1242-1245]	8.35-13	4-5 modes	3.3	80	1000	0.4	superradiant
	35	TE ₆₂	0.78	1.6 (3.5)	100	8 (4) ^{*)}	slotted cavity
			1.15	2.5	275	10	
35	TE ₁₃	0.9	0.65	35	6		
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. Strathelyde [1249-1254]	23	TE ₁₂	0.1	0.5	5	10	
	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	Frequency [GHz]	Mode	Harmonic No. s	Voltage [MV]	Current [kA]	Power [MW]	Efficiency [%]
IAP, Nizhny Novgorod [485,1173,1255-1263]	21.6	TE ₁₁	1	0.3	0.03 (3)	1.5	16.7 (0.17)
	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 ($\tau = 10$ μ s, 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 [122,123,450,1265]	90.8	TEM _{00q}	150	15	5	grating output
	100	TEM _{00q}	90	15	15	
	200 (2Ω _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 ₀₆₁ ⁰	83	18	0.003	confocal
	114.3	HE ₀₅₁ ⁰	75	16	0.003	slot-cavity
Moscow-State UNIV. [1270]	35	TEM _{00q}	1	15	CW	
	95	TEM _{00q}	1	15	CW	
NRL, Washington D.C. [1001,1271,1272]	110	TEM _{00q}	80	8	0.013	
	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 [694]	112	TEM _{00q}	100	12	5	
	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 (2Ω _c)	HE _{011,1} ⁰	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 (2Ω _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)	superradiance
IAP	38	TE ₁₁ */TE ₂₁ (2Ω _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 (2Ω _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-TWTs, 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	TE ₀₁	4	10.1	33.5	32	0.45	(92 kW, 11% duty) (102 kW, 10% duty)
	94.2	TE ₀₁	5	10.2	31	33	0.75	
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 Gyroklystrons

Institution	Frequency [GHz]	Mode output	No. of cavities	Power [MW]	Efficiency [%]	Gain [dB]	BW [%]	Type
IAP, Nizhny Novgorod, Saratov State UNIV. [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 (2Ω _c)	TE ₀₂	3	27	13	25	0.1	coaxial
			4	18.5	7.0	23.3	0.35	coaxial
	19.76 (2Ω _c)	TE ₀₂	2	32	29	27	0.1	
29.57 (3Ω _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 (2Ω _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 (2Ω _c)	TE ₋₂₁ /TE ₊₁₁	180	27	25	10	cusped gun with axis-encircl. beam 3 μs
	34.3 (2Ω _c)	TE ₋₂₁ /TE ₊₁₁	120	23	20	6	longpulse 110 μs
	96.2 (2Ω _c)	TE ₋₂₁ /TE ₊₁₁	160 (7.7) 3	40 (26) SDC 15 (SDC)	23 (26) 54	7.7 (7.5) 2.3	100 μs pulse (CW) 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 ₀₆₁ ⁰ (q.o.)	30	12.5	29	1.6	at 0.875 kW 400 ps modulation pulse
	250	TE ₀₃ -like	0.55 0.045	0.4 0.4	35 38	0.9 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 (3Ω _c)	TE ₃₁	6	5	11	3	axis-encircl. beam
	15.7 (2Ω _c)	TE ₂₁	207	12.9	16	2.1	slotted waveguide
	16.2 (8Ω _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 (2Ω _c)	TE ₋₂₁ /TE ₊₁₁	3.4	4.2	37	5.8	cusped 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(ΔB)	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	TE ₁₀	TE ₁₀	73	22.5	37	1.5
	31.5	TE ₄₂ ($2\Omega_c$)	TE ₄₂	160	25	30	1.3
	93.5	TE ₀₁ (3 cav.)	TE ₀₁	48	17.5	30	2.0
IAP, N.Novgorod, NRL Washington D.C. [1509,1510]	9.2	TE ₀₁ (2 cav.)	TE ₀₁	4.8	14	20	0.9
				4.4	27.5	18	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	TW section	Power [kW]	Efficiency [%]	Gain [dB]	BW [%]
IECAS [1511-1518]	33.1	TE ₀₁ /coupled cavity (2Ω _c) TE ₀₂ /TE ₀₃	TE ₀₃ (Ω _c)	75	7.1	25	1.1
Seoul National UNIV. [1519]	33.9	TE ₁₀	TE ₁₀ (3Ω _c)	10 ⁻⁴	2 · 10 ⁻³	LO-gyro-TWT	3.8
UNIV. Maryland. [484,1520-1525]	31.8	TE ₂₂	TE ₄₂ (2Ω _c)	100	20	30	1.3
	33.7	TE ₀₂	TE ₀₃ (2Ω _c)	430	35	30	0.3
	34.6	TE ₀₂	TE ₀₃ (2Ω _c)	180	32	30	3.0
	32.5	TE ₀₂	TE ₀₃ (2Ω _c)	200	12	phase-locked oscillator 36	3.0
	35	TE ₀₂ /TE ₀₃ (2Ω _c)	TE ₀₄ (2Ω _c)	110	32	gyro-TWT 53	3.0
	33.75	Gyrotriotron		126	12	gyro-TWT 27	3.2

TWT input stage (s₁=1) TE₀₂ / 4-unit clustered cavities (s₂=2) TE₀₃ / TWT output stage (s₃ = 2) TE₀₄

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

Relativistic Pulse Gyrotwystrons

Institution	Frequency [GHz]	Mode cavity	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 (2Ω _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 23 (SDC)	5	MIG CW operation
IAP, Nizhny Novgorod [1389,1401]	35-38 ($2\Omega_c$) 35 ($2\Omega_c$) 96 ($2\Omega_c$)	TE_{+21}/TE_{-11} TE_{+21}/TE_{-11} TE_{+21}/TE_{-11}	34 10 1.3	7 7	15 15 4.2	quasi-Pierce gun with kicker cusp gun with thermal cathode cusp gun with thermal cathode two-tubes cascade
IECAS, BVERI, Beijing [1533,1534]	17.2	TE_{01}	48	10.5 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 29.2	TE_{10}^r TE_{10}^r	2 6	9 15	3 13	electric tuning magnetic tuning
NTHU, Hsinchu [1537-1545]	k33.5	TE_{11}^c TE_{01}^c TE_{02}^c	20-67 115 149 154 164 123 2.8	6.5-21.7 23 30 39 41 24.5 22.6	5 8.5 4 1 1 15.8 9.5	injection locked free running electric + magnetic tuning injection locked inverse injec. locked sliced circuit 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 35($2\Omega_c$)	TM_{11} TE_{-21}/TE_{+11}	200 1.15	22 10 axis	15 (ΔB) encircling	0.45 0.35 e-beam	2 0.032	Cherenkov with cycl. mode selection 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 5-6 ($2\Omega_c$)	TE_{11} TE_{11}	55 (30) 1	8 (4.3) 0.15	1 4	0.7	1	
USAF Phillips Lab. Aberdeen [1559,1560]	4.2 4.4	TE_{21} TE_{01}	4 0.15	1 0.04	1 1	0.4 0.4	1 1	

r = rectangular waveguide

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

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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. Emphasis is on high-power gyrotron oscillators for long-pulse or continuous wave (CW) operation and pulsed gyrotrons for many 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 and single-stage depressed collectors is 30 minutes (CPI USA and European KIT-SPC-THALES collaboration). PLL-frequency stabilization of such tubes has been demonstrated. A 1.5 MW version of this gyrotron is under development (IPP-KIT-THALES). 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 (max. pulse duration 50 ms) achieved in 1 ms pulses the record power of 2.2 MW at 48% efficiency and 96% Gaussian mode purity.