State-of-the-Art of High-Power Gyro-Devices: 2025 Update of Experimental Results

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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-fre-quency gyrotrons; coaxial-cavity multi-megawatt gyrotrons; complex two-section stepped cavity gyrotrons; gyrotrons for technological and spectroscopy applica-tions; 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 oscil-lators (“gyromonotrons or just gyrotrons”) are mainly used as high-power millim-eter-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. Megawatt-class gyrotrons employ synthetic-diamond output windows and single-stage depressed collectors (SDCs) for electron energy recovery. The maximum pulse length of the 140 GHz, 1.3 MW IPP-KIT-THALES gyrotron is 3 min (1.2 MW/6 min) at 97.5% Gaussian output mode purity and 47% efficiency. The 1 MW version of this tube operates at pulse lengths up to 30 min, and PLL-frequency stabilization has been demonstrated. The first Japan QST-CANON 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 very high-order-mode Russian 170 GHz-1 MW gyrotron (IAP) has been demonstrated in short pulses using a PLL-frequency-stabilized 20 kW gyrotron master oscillator. A Russian short-pulse 74.2 GHz, 100 kW gyrotron (SPbSTU) with 4-stage depressed collector achieved an efficiency of 72%.

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 and was operated at pulse lengths up to 50 ms. 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, $P_{out} = 4$–50 kW, CW, $\eta \geq 30\%$. Gyrotrons with pulsed magnet for various short-pulse applications deliver $P_{out} = 210$ kW with $\tau = 20$ μs 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 20 kW, respectively.

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

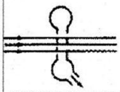
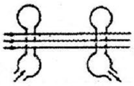
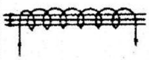
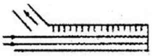
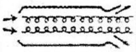
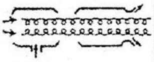
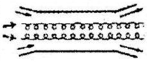
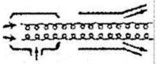
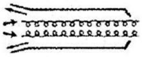
1 Introduction

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, material processing, and plasma chemistry.

Most works on ECM devices have investigated the conventional gyrotron [9–32] 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 0.1–1.3 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 [33–67] and stellarators [67–97]. The confining magnetic fields in present day fusion devices are in the range of $B_o = 1$–3.6 T. As fusion machines become larger and operate at

Table 1 Overview of different types of gyro-devices and comparison with corresponding conventional linear-beam (O-type) microwave tubes

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

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 and 170 GHz [23, 26–31, 40, 59–63, 68–90, 96–121]. 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 [102–117] 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, 40, 103–126]. Frequency tuning has been shown to be possible in quasi-optical Fabry–Perot cavity gyrotrons [127, 128] as well as in cylindrical and coaxial cavity gyrotrons by frequency tuning in steps (different operating cavity modes) [129–164].

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 [165–194] (Tables 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, and 13), the development of very high frequency gyrotrons for active plasma diagnostics [195–252], 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) [253–375], remote detection of concealed radioactive materials [376–379], wireless communication [380], and medical applications [381–386] (Tables 14, 15, 16, 17, and 18). 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, 387–417]. 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 [418] and Gycom in Russia [395, 406–409, 419–424] 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 [1143–1146]. 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 [1147–1160]. Therefore, this report also gives an overview of the present development status of relativistic and quasi-optical gyrotrons (Tables 20, 21, and 22), fast- and slow-wave cyclotron autoresonance masers (CARMs) [1161–1165] (Tables 23 and 24), gyro-klystrons (Tables 25, 26, and 27), gyrotron travelling wave tube amplifiers (Gyro-TWTs) (Tables 28 and 29), gyrotwystron amplifiers (Tables 30, 31, and 32) [741, 1166–1171], and broadband gyrotron backward wave oscillators (Gyro-BWOs) (Tables 33 and 34).

The list of references includes additional information about principle and history of gyrotrons [425, 478, 585, 658, 1172–1184], effective cavity length [1185], internal quasi-optical mode converters as transverse Gaussian beam or HE_{11} mode output couplers [1186–1202], electron beam space-charge neutralization [1203, 1204], other gyro-devices and peniotrons [1205–1216], magnicons [1217–1232], and gyro-harmonic converters [1233–1235].

Table 2 Performance parameters of gyrotron oscillators with frequencies between 5 and 95 GHz (see also Table 8)

Institution	Frequency (GHz)	Mode		Power (MW)	Efficiency (%)	Pulse length (s)
		Cavity	Output			
ABB, Baden [425, 426]	8/39	TE_{01}/TE_{02}	TE_{01}/TE_{02}	0.35/0.25	35/42	0.5/0.1
ARIEL UNIV., Ariel [427–434]	27, 28, 31, 35, 39	$TE_{11,21,01,02}$	$TE_{11,21,01,02}$	0.004–0.035	11–36.4	0.000020
	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 [435]	42	TE_{03}	TE_{03}	0.126	20.4	0.0005
CPI/MPP[a], Palo Alto	8	TE_{21}	TE_{10}	0.5 (dual output) 33		1.0
[15, 20, 436–454]	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)
	94.9/95.3	$TE_{6,2}/TE_{22,6}$	TEM_{00}	0.12/0.63 (1.92)	50/42 (40)(SDC)	CW/15 (0.005)
CPI/MPP[a], NIFS, Palo Alto, Toki	84	$TE_{15,3}$	TEM_{00}	0.5(0.4)/0.1	29/14	2.0(10.5)/CW
[91, 92, 439–443, 455–458]				0.59(0.25)	41(32) (SDC)	0.001(0.2)
GYCOM, IAP	5	TE_{01}	TE_{01}	0.23	26	0.1
Nizhny Novgorod	25 ($2\Omega_c$)	TE_{03}	TE_{03}	0.8/0.87	40/25(2e-beams)	0.0001
[16, 130, 131, 149–156, 459–477]	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)	35.3 (24.9)	0.0001

Table 2 (continued)

Institution	Frequency (GHz)	Mode		Power (MW)	Efficiency (%)	Pulse length (s)
		Cavity	Output			
	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 [478]	60	TE_{02}	TE_{02}	0.2	35	0.1
IECAS, Beijing [479–483]	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 [484, 485]	94	TE_{01}	TE_{01}	0.008	9.5	0.1
IAE-CAEP, Mianyang [486–494]	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(2Ω_c)/95(3Ω_c)	TE_{02}/TE_{61}	TEM_{11}/TE_{61}	0.012/0.006	24 (SDC)/4	300/0.0001
KERI, Changwon [495, 496]	94.5	$TE_{6,2}$	TEM_{00}	0.1/0.037	33/48 (SDC)	0.00005/2
LAP/INPE, Sao Paulo [497]	24.2/30.4	TE_{12} /TE_{22}	TE_{12} /TE_{22}	0.0058/0.0063	16/18.5	0.000015
MITSUBISHI, Amagasaki	88	$TE_{8,2}$	TEM_{00}	0.35	29	0.1
KYOTO UNIV. [498]						
NEC, Kawasaki [499]	35	TE_{01}	TE_{01}	0.1	30	0.001
NRL, Washington D.C	35	TE_{01}	TE_{01}	0.15	31	0.02
[478, 500–502]	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[b], Hamburg [503]	70	TE_{02}	TE_{02}	0.21(0.14)	38(30)	0.1(CW)
SPbSTU, St. Petersburg and KIT[c]	74.2	$TE_{12,3}$	$TE_{12,3}$	0.1	44	0.00005
Karlsruhe [504–512], SPbSTU				0.1	72 (MDC)	0.00002
THALES[d], Velizy [425, 513]	8	$TE_{5,1}$	$TE_{5,1}$	1.0	45	1.0

Table 2 (continued)

Institution	Frequency (GHz)	Mode		Power (MW)	Efficiency (%)	Pulse length (s)
		Cavity	Output			
	35	TE_{02}	TE_{02}	0.335	43	0.15
TSUKUBA UNIV., QST, CANON[e]	28	TE_{02}	TE_{02}	0.2	35.7	0.075
Ibaraki, Otawara [94–96, 514–528]	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 [483, 529–537]	15	TE_{01}	TEM_{00}	0.1	30	0.0001
	35 ($3\Omega_c$)	TE_{51}/TE_{52}	TE_{52}	0.147	10.2	0.0001 PM, 100 kg
	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, CANON[e] [499]	70	TE_{02}	TE_{02}	0.025	28.4	0.001
UNIST, Ulsan [538]	95	TE_{62}	TEM_{00}	0.062	22	0.000003

SDC (MDC) single-stage (multi-stage) depressed collector, *PM* permanent magnet

[a] Communications and Power Industries/MPP, formerly VARIAN

[b] Formerly VALVO

[c] Karlsruhe Institute of Technology, formerly FZK

[d] TED, formerly Thomson TE

[e] Formerly TOSHIBA

Table 3 Present development status of high frequency gyrotron oscillators for ECH&CD and stability control in magnetic fusion devices ($100\ \text{GHz} \leq f < 140\ \text{GHz}$, $\tau \geq 0.1$ ms) (see also Table 8)

Institution	Frequency (GHz)	Mode		Power (MW)	Efficiency (%)	Pulse length (s)
		Cavity	Output			
CPI/MPP[a], Palo Alto	106.4($2\Omega_c$)	$TE_{02/03}$	TE_{03}	0.135	21	0.1
[15, 58, 293, 437–441, 450–453, 539–564]	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 1.2/0.95/0.55	37 (SDC) 34 (SDC)	0.001 0.4/5.0/10.0
KIT[b], Karlsruhe	117.9	$TE_{19,5}$	TEM_{00}	1.55	31	0.007
[132–144, 565–584]				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, 466, 585–595]				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, 130, 131, 145–164, 462–467, 596–600]	105	$TE_{17,6}$	TEM_{00}	1.04/0.85	57/50 (SDC)	10/300
	105	$TE_{17,4/17,7}$	$TE_{17,7}$	0.26	26	0.00003
	106	$TE_{14,5/14,8}$	$TE_{14,8}$	0.24	22	0.00003

Table 3 (continued)

Institution	Frequency (GHz)	Mode		Power (MW)	Efficiency (%)	Pulse length (s)
		Cavity	Output			
	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[c], CANON[d]	104.1	$TE_{19,7}$	TEM_{00}	0.9	41 (SDC)	300
Naka, Otawara [23, 525–528, 601–629]	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
[630, 631]	120	$TE_{15,2}$	$TE_{15,2}$	1.02	32.5	0.0002
				0.46 (0.25)	30	0.1 (0.21)
THALES[e], Velizy	100	TE_{34}	TE_{34}	0.19	30	0.07
[425, 513]	110	TE_{93}	TE_{93}	0.42	17.5	0.002

Table 3 (continued)

Institution	Frequency (GHz)	Mode		Power (MW)	Efficiency (%)	Pulse length (s)
		Cavity	Output			
	110	TE_{64}	TE_{64}	0.34	19	0.01
				0.39	19.5	0.21
THALES[e], CEA, SPC[f], KIT[b] [632–642]	105	$TE_{20,8}$	TEM_{00}	1.2/1.0	35/45 (SDC)	0.001/5.0
	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

[a] Communications & Power Industries/Microwave Power Products (CPI/MPP), formerly VARIAN

[b] Formerly KfK, then FZK

[c] Formerly JAERI, then JAEA

[d] Formerly TOSHIBA

[e] Formerly Thomson TE

[f] Formerly CRPP

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) (see also Table 8)

Institution	Frequency (GHz)	Mode		Power (MW)	Efficiency (%)	Pulse length (s)
		Cavity	Output			
BVERI, Beijing [643–646]	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}	0.71	20.4	0.001
CPI[a], Palo Alto	140	$TE_{02/03}$	TE_{03}	0.1	27	CW
[15, 20, 293, 437–441, 450, 452, 453, 548–552, 555–559, 561–563, 647–652]	140	$TE_{15,2}$	$TE_{15,2}$	1.04(0.32)	38 (31)	0.0005(3.6)
				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 [653, 654]	140	$TE_{7,3}$	TEM_{00}	0.030/0.052	34/39.4 (SDC)	60/30
IE and IPP, Hefei [655, 656]	169.6	$TE_{25,10}$	TEM_{00}	0.52/0.23/0.13	44 (SDC)	0.2/4.9/20
KIT[b], PHILIPS[c] [425, 657]	140.8	TE_{03}	TE_{03}	0.12	26	0.4
KIT[b], Karlsruhe	140.2	$TE_{10,4}$	$TE_{10,4}$	0.69	28	0.005
[132–144, 565–584, 658–674]	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[b], IPP[d], SPC[e], THALES[f]	139.8	$TE_{28,8}$	TEM_{00}	1.0/0.92	50/44 (SDC)	12/1800
[6, 7, 73–85, 100–109, 635, 675–723]	140.3	$TE_{28,10}$	TEM_{00}	1.6/1.3/1.2	47/46/45 (SDC)	0.001/180/580
EGYC[g] [724–740]	170	$TE_{32,9}$	TEM_{00}	1.5 1.02/0.96/0.70	33/50 (SDC) 41/38/41 (SDC)	0.001 100/1000//1580
GYCOM, IAP	140	$TE_{22,6}$	TEM_{00}	0.96	36	1.2

Table 4 (continued)

Institution	Frequency (GHz)	Mode		Power (MW)	Efficiency (%)	Pulse length (s)
		Cavity	Output			
Nizhny Novgorod				0.54	36	3.0
[16, 145–164, 463–467, 588–595, 600, [741–781]				0.26 (0.1)	36	10 (80)
		(dual-beam	output)	2×0.37	30	3.0
				2×0.3	29	5.5
				2×0.165	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, 130, 131, 462–464, 467, 471, 593–595, 598, 599, 742, 757, 781–788]				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[h], CANON[i]	170	$TE_{22,6}$	TEM_{00}	0.45	19	0.05
Naka, Otawara				0.25	32 (SDC)	0.4
[23, 607–622, 789–836]	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

Table 4 (continued)

Institution	Frequency (GHz)	Mode		Power (MW)	Efficiency (%)	Pulse length (s)
		Cavity	Output			
				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	47/51 (SDC)	2.0/1000
QST[h], TSUKUBA UNIV., CANON[i] [526–528, 837–840]	300	$TE_{32,18}$	$TE_{32,18}$	0.52/0.62	20	0.002/0.001 tilted SiO_2 window
NIFS, TSUKUBA UNIV., CANON[h]	154	$TE_{28,8}$	TEM_{00}	1.25	37 (SDC)	0.004
				0.35	39 (SDC)	1800
Toki, Ibaraki, Otawara	168	$TE_{31,8}$	TEM_{00}	0.52	19	1.0
[91–94, 458, 522, 524–528, 841–843]				0.52	30 (SDC)	1.0

SDC single-stage depressed collector

[a] CPI/MPP, formerly VARIAN

[b] Formerly KfK, then FZK

[c] Formerly VALVO

[d] IPP Greifswald

[e] Formerly CRPP

[f] Formerly Thomson TE

[g] EGYC collaboration among SPC, Switzerland; KIT, Germany; HELLAS, Greece; CNR, Italy; ENEA Italy

[h] Formerly JAERI, then JAEA

[i] Formerly TOSHIBA

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 [844–847]. 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 (%)	Corrug.Cavity	
		Cavity	Output			Inner	Outer
KIT[a] Karlsruhe	137.78	$TE_{27,16}$	$TE_{27,16}$	1.03	24.3	Yes	No
[6, 23, 26–29, 103–105, 669–675, 691, 848–868]	139.96	$TE_{28,16}$	$TE_{28,16}$	1.17	27.2	Yes	No[c]
		$TE_{28,16}$	$TE_{76,2}$/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
		$TE_{31,17}$	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[b], KIT[a] [26–30, 106–117, 869–906]	170	$TE_{34,19}$	TEM_{00}	2.1 (1 ms)	48 (SDC)	Yes	No
Pulse length ≤ 100 ms				2.1/1.5 (11/35 ms)	47/42 (SDC)	Yes	No
IAP, Nizhny Novgorod	15/45	$TE_{9,1}$/$TE_{15,1}$	$TE_{9,1}$/$TE_{15,1}$	0.38/1.25	30/35	No/no	No/no
[11, 14, 16, 122, 463, 466, 907–915]	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

Table 5 (continued)

Institution	Frequency (GHz)	Mode		Power (MW)	Efficiency (%)	Corrug.Cavity	
		Cavity	Output			Inner	Outer
				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[c]
				1.15	50 (SDC)	Yes	No
		$TE_{28,16}$	$TE_{76,2}$	1.17	35.2	Yes	Yes
			TEM_{00}	1.1	30	Yes	No
				(Dual-beam output)			
	224 ($2\Omega_c$)	$TE_{33,8}$	$TE_{33,8}$	0.11	14	Yes	No
IAP, KIT[a] Karlsruhe [848]	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 [916–919]	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 [920]	110/220 ($2\Omega_c$) Two electron beams	TE_{02}/TE_{04}	TEM_{00}	0.02	5	No	No

[a] Formerly KfK, then FZK

[b] EGYC is a collaboration among SPC, Switzerland; KIT, Germany; HELLAS, Greece; CNR, Italy; ENEA Italy

[c] Very similar cavity and tube design

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		Power (MW)	Efficiency (%)	Pulse length (s)
		Cavity	Output			
CPI/MPP[a], Palo Alto	8	TE_{21}	TE_{10}	0.4	26.6	0.0005
[27, 30, 436–454, 543–552, 555–564, 647–652]	(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}	1.28/0.52	42.3/29(SDC)	0.001/10
	140.2	$TE_{27,8}$	TEM_{00}	0.92/0.9	36/33 (SDC)	0.003/1800
IAE-CAEP, Mianyang [486–494, 653, 654]	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[a], NIFS	84	$TE_{15,3}$	TEM_{00}	0.5	29	2.0
Palo Alto, Toki [91–94, 442]				0.59/0.25	41/32 (SDC)	0.001/2
IE and IPP, Hefei [655, 656]	169.6	$TE_{25,10}$	TEM_{00}	0.52/0.23/0.13	44 (SDC)	0.2/4.9/20
KIT[b], Karlsruhe	117.9	$TE_{19,5}$	TEM_{00}	1.55	49.5 (SDC)	0.007
[24, 132–139, 565–584, 664–675]	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[b], IPP[c], SPC[d], EGYC[e], CEA, THALES[f], [7, 27, 30, 74–78, 103–118, 635, 641, 675–740]	105	$TE_{20,8}$	TEM_{00}	1.2/1.0	35/45(SDC)	0.001/5.0
	139.8	$TE_{28,8}$	TEM_{00}	1.0/0.92	50/44 (SDC)	12/1800
	140.3	$TE_{28,10}$	TEM_{00}	1.6/1.3/1.2	47/46/45 (SDC)	0.001/180/580
	170	$TE_{32,9}$	TEM_{00}	1.0/0.96/07	41/38/41 (SDC)	100/1000/1580

Table 6 (continued)

Institution	Frequency (GHz)	Mode		Power (MW)	Efficiency (%)	Pulse length (s)
		Cavity	Output			
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
[463–466, 469–472, 477, 589, 590, 595, 597]	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, 145–164, 471, 746–778, 781]	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 [495, 496]	94.5	$TE_{6,2}$	TEM_{00}	0.1/0.037	33/48 (SDC)	0.00005/2
NRL, Washington D.C [921]	115	QOG	TEM_{00}	0.43	12.7 (SDC)	10^{-5}
				0.20	16.1 (SDC)	10^{-5}
QST[g], CANON[h]	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, 604–629, 789–836, 839, 840]	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

Table 6 (continued)

Institution	Frequency (GHz)	Mode		Power (MW)	Efficiency (%)	Pulse length (s)
		Cavity	Output			
	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	47/51 SDC	2.0/1000
NIFS, TSUKUBA UNIV., CANON[h]	77	$TE_{18,6}$	TEM_{00}	1.9	38 (SDC)	0.1
Toki, Ibaraki, Otawara [27, 30, 91–97, 458, 517–528, 840–843]				1.8/1.6/1.2/0.22	38 (SDC)	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	19/30 (SDC)	1.0

SDC single-stage depressed collector, *QOG* quasi-optical gyrotron

[a] Formerly VARIAN

[b] Formerly KfK, then FZK

[c] IPP Greifswald

[d] Formerly CRPP

[e] EGYC collaboration among SPC, Switzerland; KIT, Germany; HELLAS, Greece; CNR, Italy; ENEA Italy

[f] Formerly Thomson TE

[g] Formerly JAERI, then JAEA

[h] 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 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% [922]

Institution	Frequency (GHz)	Mode		Power (MW)	Efficiency (%)	Pulse length (s)	
		Cavity	Output				
KIT[a], Karlsruhe	114.2	$TE_{18,5}$	TEM_{00}	0.85	23	0.001	
[27–30, 132–144, 570, 573, 575–584]	117.9	$TE_{19,5}$	TEM_{00}	1.0	27	0.001	
				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	

Table 7 (continued)

Institution	Frequency (GHz)	Mode		Power (MW)	Efficiency (%)	Pulse length (s)	
		Cavity	Output				
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, 130, 131, 145–164, 466, 468–471, 595, 922, 923]	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[b], CANON[c]	166.7	$TE_{30,8}$	TEM_{00}	0.54	27	0.001	Plane window
Naka, Otawara [27, 30, 810, 924]	170	$TE_{31,8}$	TEM_{00}	0.62	32	0.001	Plane window

Table 7 (continued)

Institution	Frequency (GHz)	Mode		Power (MW)	Efficiency (%)	Pulse length (s)	
		Cavity	Output				
QST[b], TSUKUBA, CANON[c] Naka, Ibaraki, Otawara [30, 838, 839]	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	107.1	$TE_{21,6}$	TEM_{00}	1.1	30	0.000003	Plane window
[925–934]	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

[a] Formerly KfK, then FZK

[b] Formerly JAERI, then JAEA

[c] 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 [138]. 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 [924]

Institution	Frequency (GHz)	Mode		Power (MW)	Efficiency (%)	Pulse length (s)	No. of frequencies
		Cavity	Output				
CPI/MPP[a], Palo Alto [563]	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[b], SPC[c], EGYC[d], THALES[e] [27–30, 697, 935–938]	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
	103.8/101.25	$TE_{21,6}$/ $TE_{20,6}$	TEM_{00}	0.41/0.31	27 (SDC)	10/0.06	3f-Gyrotron
	140.0	$TE_{28,8}$	TEM_{00}	0.92	44 (SDC)	1800	3f-Gyrotron
	171/174	$TE_{33,10}$/$TE_{34,10}$	TEM_{00}	0.4	30 (SDC)	0.01	3f-Gyrotron
GYCOM, IAP Nizhny Novgorod [27–30, 41–57, 147–164, 467, 471, 595, 598–600, 758–778, 923, 939]	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}	1.14/095	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 [940–942]	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[f], CANON[g] Naka, Otawara [27, 30, 802, 810, 814–830, 833, 835, 836, 924, 943–945]	104.1	$TE_{19,7}$	TEM_{00}	0.9	41 (SDC)	300	4f-Gyrotron

Table 8 (continued)

Institution	Frequency (GHz)	Mode		Power (MW)	Efficiency (%)	Pulse length (s)	No. of frequencies
		Cavity	Output				
	136.8	$TE_{25,9}$	TEM_{00}	1.0/	44 (SDC)	300	4f-Gyrotron
	170	$TE_{31,11}$	TEM_{00}	1.2/1.0	47/50 SDC	5/1000	4f-Gyrotron
	203	$TE_{37,13}$	TEM_{00}	1.0/0.6	50 (SDC)	3/10	4f-Gyrotron
QST[f], CANON[g] Naka, Otawara [528, 623–629]	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., KYOTO FUSIONEERING, UKAEA, CANON[g] Toki, Ibaraki, Kyoto, Abingdon, Otawara [526, 527, 629, 839–843, 946, 947]	28.04	$TE_{8,5}$	TEM_{00}	1.65	31	0.002	2f-Gyrotron
	34.83	$TE_{10,6}$	TEM_{00}	1.21/0.94	27/41.5 (SDC)	0.002/3.0	2f-Gyrotron
	115.5	$TE_{21,7}$	TEM_{00}				2f-Gyrotron
	154	$TE_{28,9}$	TEM_{00}				2f-Gyrotron

SDC single-stage depressed collector

[a] Formerly VARIAN

[b] Formerly KfK, then FZK

[c] Formerly CRPP

[d] EGYC collaboration among SPC, Switzerland; KIT, Germany; HELLAS, Greece; CNR, Italy; ENEA Italy

[e] Formerly Thomson TE

[f] Formerly JAERI, then JAEA

[g] Formerly TOSHIBA

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 [911–914]. 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 [864]

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[a], Karlsruhe [137, 856–859, 862–865]	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

Table 9 (continued)

Institution	Frequency (GHz)	Mode		Power (MW)	Efficiency (%)	Pulse length (s)
		Cavity	Output			
				1.24	41 (SDC)	0.001
	167.2	$TE_{32,17}$	TEM_{00}	1.22	25.6	0.001
EGYC[b] [888–891, 895, 898]	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

[a] Formerly KfK, then FZK

[b] EGYC is a collaboration among SPC (formerly CRPP), Switzerland; KIT, Germany; HELLAS, Greece; CNR, Italy; ENEA Italy

Table 10 Experimental parameters of high-power millimeter-wave vacuum windows [15, 16, 20, 23–30, 149–164, 425, 438–454, 458, 466, 471, 472, 517–528, 539–652, 658, 679–740, 742–840, 924, 935–997]

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[a]
Sapphire	Single-disk LN_2 edge cooled	530	118	5.0	CEA/SPC/KIT/THALES
		350	118	111	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[a]
		500	110	0.5	QST/GA
Sapphire	Double-disk FC75 face cooled	200	28	CW	CPI

Table 10 (continued)

Material	Type	Power (kW)	Frequency (GHz)	Pulse length (s)	Institution
		200	35	CW	CPI
		200	60	CW	CPI
		400	84	10.5	NIFS/CPI
		350	110	5.0	QST/CANON[a]
		200	140	CW	CPI
		500	170	0.6	QST/CANON[a]
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[a]
		600	70	2.3	CPI
		1.2	77	10	NIFS/TSUKUBA/CANON[a]
		0.3	77	CW	NIFS/TSUKUBA/CANON[a]
		500	84	2.0	CPI
		120	94	CW	CPI
		900	104	300	QST/CANON[a]
		850	105	300	IAP/GYCOM
		300**	110	1.0	CPI/FOM
		50	110	CW	CPI/FOM
		450	110	2.0	IAP/GYCOM/GA
		1050	110	5.0	CPI/GA

Table 10 (continued)

Material	Type	Power (kW)	Frequency (GHz)	Pulse length (s)	Institution
		600	110	10	CPI/GA
		1500	110	4.0	QST/CANON[a]
		1000	110	100	QST/CANON[a]
		340	118	50	KIT/CEA/THALES
		300	118	111	KIT/CEA/THALES
		1000	137	300	QST/CANON[a]
		1200/1300	140	580/180	KIT/SPC/TED
		920	140	1800	KIT/SPC/TED
		900	140	1800	CPI
		1140/950/700	140	10/300/3000	IAP/GYCOM
		350	154	1800	NIFS/TSUKUBA/CANON[a]
		1500	170	2.5	IAP/GYCOM
		1200	170	500	IAP/GYCOM
		1000	170	1000	IAP/GYCOM
		1000/800	170	1000/3600	QST/CANON[a]
		1000/600	203	3/10	QST/CANON[a]

* and ** indicates that the power corresponds to that of a 1 MW (*) and 0.8 MW (**) HE_{11} mode

[a] Formerly TOSHIBA

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) [100, 123, 969, 975, 979, 982, 984, 992–996, 998–1002]

Material	BeO p.c.	BN (CVD) p.c.	Si_3N_4 composite (SN-287)	Sapphire (Al_20_3) s.c. orientation of E $c \perp \vec{E}$	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 v	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 δ (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 Ø (mm)	150	145	300	270	127	120	
Cost	Medium	Medium	High	High	Low	Very high	Medium
Failure resistance R (W/mm^2) $R' = k\sigma_B\,(1\text{-}v)/E\alpha$	10.3	15.7	44.5	6.0	284	772	40
RF-power capacity P_T (100 W^{2}s/mm^{4}K) $P_T = R'\rho\, c_P/((1+\varepsilon_r')\tan\delta)$	0.06	0.05	0.36	0.09	106	106	0.63
Radiation sensitivity							
n (10^{20}–10^{21} n/m^2)				No	No	No	
γ/X (0.75 Gy/s)				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) [969]

Material	Sapphire (Al$_2$0$_3$) s.c. orientation of E c$\perp\vec{E}$	Silicon Au-doped s.c.	Diamond (PACVD) p.c.
Thermal conductivity k (W/mK)	900 (20,000)	1300	10,000
Ultimate bending strength σ_B (MPa)	410	1000	450
Poissons number v	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 δ (10^{-5})	0.57 (0.2)	0.35	2
Metallizing and brazing bakeout temperature	o.k	o.k	o.k
	550 °C	550 °C	450 °C
Possible size Ø (mm)	270	127	160
Cost	High	Low	Very high
Failure resistance R' (W/mm^2) $R' = k\sigma_B\,(1-v)/E\alpha$	130 (2871)	2463	3214
RF-power capacity P_T (100 W^{2}s/mm^{4}K) $P_T = R'\rho\, c_P/((1+\varepsilon_r')\tan\delta)$	71 (4460)	907	441
Radiation sensitivity			
n (0.3–10^{21} n/m^2)	No	No	No
γ/X (0.75 Gy/s)	No	No	No

Table 13 Options for 1 MW, CW, 170 GHz gyrotron windows [98–103, 123, 969]. First operation of a wideband short-pulse D-band megawatt gyrotron with elliptically brazed CVD-diamond Brewster window was published in [140–142]. 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 [1003–1005]. Large area diamond disk growth experiments (180 mm diameter) and thermo-mechanical investigations for Brewster windows are published in [1006]. Broadband CVD-diamond Brewster windows are also developed for use in gyro-amplifiers [1007, 1008]

	Material	Type	RF-profile	Cross-section	Cooling
①	Sapphire/Metal	Distributed	Flattened Gaussian	Rectangular (100 mm × 100 mm)	Internally water cooled (300 K) $\tan\delta = 2–5 \times 10^{-4}$, $k = 40$ W/mK
②	Diamond	Single-disk	Gaussian	Circular (∅ = 80 mm)	Water edge cooled (300 K) $\tan\delta = 2 \times 10^{-5}$, $k = 1900$ W/mK
③	Diamond	Single-disk Brewster	Gaussian	Elliptical (152 mm × 63.5 mm)	Water edge cooled (300 K) $\tan\delta = 2 \times 10^{-5}$, $k = 1900$ W/mK
④	Silicon Au-doped	Single-disk	Gaussian	Circular (∅ = 80 mm)	Edge cooled (230 K), refrigerator $\tan\delta = 2.5 \times 10^{-6}$, $k = 300$ W/mK
⑤	Silicon Au-doped	Single-disk	Gaussian	Circular (∅ = 80 mm)	LN_2 edge cooled (77 K) $\tan\delta = 4 \times 10^{-6}$, $k = 1500$ W/mK
⑥	Sapphire	Single disk	Flattened Gaussian	Elliptical (285 mm × 35 mm)	LN_2 edge cooled (77 K) $\tan\delta = 6.7 \times 10^{-6}$, $k = 1000$ W/mK
⑦	Sapphire	Single disk	Gaussian	Circular (∅ = 80 mm)	LNe or LHe edge cooled (27 K) $\tan\delta = 1.9 \times 10^{-6}$, $k = 2000$ W/mK

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

3 Harmonic and Very High Frequency Gyrotron Oscillators

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	Power (kW)	Efficiency (%)	Pulse length (ms)
CPI/MPP[a], Palo Alto [1009]	250	$TE_{11,1}/TE_{11,2}$	10	3.4	0.1
IAP, N. Novgorod [195, 196, 1010–1013]					
	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 [1014–1016]	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 [1017–1026]	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

Table 14 (continued)

Institution	Frequency (GHz)	Mode	Power (kW)	Efficiency (%)	Pulse length (ms)
	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 [212–225, 227–232, 1027–1040]	203.4	TE_{33}	1.6	16	CW
	350.3	TE_{65}	52	8.3	0.003
	384[b]/388	TE_{26} /TE_{18} /$TE_{17,2}$	3/62/83	3.7/158/13.8	1/0.003
	392.6/402[b]	TE_{85}/TE_{55}	60/2	9.6/3	0.004/!
	576[b]	TE_{26}	1	2.5	0.5
	874[b]	TE_{19}	0.6	2.0	0.5

[a] CPI/MPP: formerly VARIAN

[b] In collaboration with TOSHIBA, Ottawara

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	Harmonic no. s	Power (kW)	Efficiency (%)	Pulse length (ms)
UNIVERSITY, Fukui IAP, Nizhny Novgorod [1041–1046]	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 [202–211, 1047–1060]	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 16 Performance parameters of pulsed and CW millimeter- and submillimeter- wave gyrotron oscillators operating at the fundamental electron cyclotron resonance with output power ≥ 1.0 kW. 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) [212–375, 1061–1070]. 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 TE03-mode [1071–1075]. 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 [1076, 1077]. A high-harmonic sectioned TE35-mode gyrotron of IAP Nizhny Novgorod produced 0.5 kW at 740 GHz with 0.9% efficiency [1078–1081]

Institution	Frequency (GHz)	Mode	Power (MW)	Efficiency (%)	Pulse length (μs)	
IAP, Nizhny Novgorod [195–201, 203–211, 350, 376, 377, 1082–1085]	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	
	263.2	$TE_{5,3}$	0.001	17	CW	CW operation
MIT, Cambridge [129, 917, 918, 1086–1101]	107.1	$TE_{21,6}$	0.94	24	3	
	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	

Table 16 (continued)

Institution	Frequency (GHz)	Mode	Power (MW)	Efficiency (%)	Pulse length (μs)	
	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 [1019, 1102–1105]	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 cathode
	228.6	TE_{52}	0.025	14.9	4	
UNIVERSITY, Fukui [27, 230, 233–249, 1028–1031, 1106]	202.9	TE_{33}	0.001	10	10,000	
	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 17 Step tuning of MIT gyrotron oscillators (with large MIG [1087, 1088]) 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 [1087, 1088]	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 18 Step tuning of MIT gyrotron oscillator (with small MIG [1087, 1088]) 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 [1087, 1088]	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 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) [395, 406, 407]. This system has been installed at the University of Fukui, Japan

Institution	Frequency (GHz)	Mode		Power (kW)	Efficiency (%)	Voltage (kV)	Magnet
		Cavity	Output				
CPI/MPP[a], Palo Alto [15, 20, 1009]	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/MPP, NIFS [91–93, 455–458] Palo Alto, Toki	84	$TE_{15,3}$	TEM_{00}	50	14	80	Cryo. Mag
GYCOM/IAP, Nizhny Novgorod [1, 16, 131, 151, 182–184, 389–392, 395, 400–415, 419–424, 463, 742, 743, 1010, 1107–1127]	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, 116 kg
	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
	31.8–34.8	TE_{11}	TE_{11}	1.2	40	12	Mech. tun

Table 19 (continued)

Institution	Frequency (GHz)	Mode		Power (kW)	Efficiency (%)	Voltage (kV)	Magnet
		Cavity	Output				
	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 [1128]	28 ($2\Omega_c$)	TE_{12}	TE_{12}	22.5	43	23.4	Room temp
MICRAMICS, San Jose [1129]	24.1 ($2\Omega_c$)	TE_{22}	TEM_{mixed}	5	25	23	Room temp
			TE_{22}	10	25	23	Room temp
MITSUBISHI, Amagasaki [418, 1130–1132]	28 ($2\Omega_c$)	TE_{02}	TE_{02}	10	38.7	21	PM, 600 kg tapered B
UESTC, Chengdu [1133, 1134]	30.2	TE_{01}	TE_{01}	0.14	11.9	4.2	Cryo. mag
	37.5	TE_{13}	TE_{13}	57 (0.4 average)	9	50.5	Room temp
UNIV. Fukui, IAP Nizhny Novgorod/GYCOM [393, 394, 1135–1142]	300	$TE_{22,8}$	TEM_{00}	2.3	16.4	14	Cryo. mag

PM permanent magnet

[a] Communications & Power Industries/Microwave Power Products, formerly VARIAN

Table 20 Present development status of relativistic gyrotron oscillators with MIG or carbon fiber array cathode

Institution	Frequency (GHz)	Mode	Voltage (MV)	Current (kA)	Power (MW)	Efficiency (%)	Type
IAP, Nizhny Novgorod [1236–1253]	9.23	TE_{01}	0.27 (0.28)	0.12 (0.06/0.045)	10 (8/7)	30 (45/50)	
	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	Explos. cath. + kicker
	35.2	$TE_{4,2}$	0.55	2	110	10	beam compression
	30.6 (35.7)	$TE_{4,2}$ ($TE_{4,2}$) $TE_{7,3}$	0.5	2	35 (40)	3.5 (4.0)	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
	107 ($3\Omega_c$)	$TE_{4,2}$	0.55	2	0.2	0.018	
IAP, Nizhny Novgorod	10	TE_{13}	0.3	0.4	25	20	Slotted cavity
Lebedev/General Phys	10	TE_{13}	0.3	1.0	60	15	Plasma-filled
Inst. Moscow [1238, 1254–1256]							Slotted cavity
	40	TE_{13}	0.4	1.3	25	5	Slotted cavity

Table 20 (continued)

Institution	Frequency (GHz)	Mode	Voltage (MV)	Current (kA)	Power (MW)	Efficiency (%)	Type
KIPT, Kharkiv [1257]	12	TE_{13}	0.12	8.0	60	6.3	Plasma filled Slotted cavity
UNIV. Michigan [1258–1264]	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
					20		Non-slott. coax. cavity
	10	TE_{11}	0.4	0.025	0.6	6	
NRL, Washington D.C. [1265–1268]	8.35–13	4–5 modes	3.3	80	1000	0.4	Super-radiant
	35	TE_{62}	0.78	1.6 (3.5)	100	8 (4)[a]	
			1.15	2.5	275	10	
	35	TE_{13}	0.9	0.65	35	6	Slotted cavity
NUDT Changsha [1269]	10.3	TE_{01} (coaxial)	0.3	0.5	11	7.3	Carbon fiber array cathode
Tomsk Polytech. Inst [1270]	3.1		0.75	8.0 (30)	1800	8	Also vircator interaction
UNIV. Niigata [1271]	18.2	TE_{01}	0.08	0.5	0.2	0.55	
UNIV. Strathclyde [1272–1277]	23	TE_{12}	0.1	0.5	5	10	
	100		0.2	0.22	6.3	14	

r rectangular waveguide

[a] 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 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)

Institution	Frequency (GHz)	Mode	Harmonic no. s	Voltage (MV)	Current (kA)	Power (MW)	Efficiency (%)
IAP, Nizhny Novgorod [1074, 1075, 1278–1287]	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 [1288]	98–144	TE_{n1}	n	0.325	0.045(7)	1.3	9(0.06)

6 Quasi-Optical Gyrotrons

Table 22 Present development status of quasi-optical gyrotron oscillators

Institution	Frequency (GHz)	Mode resonator	Power (kW)	Efficiency (%)	Pulse length (ms)	Type
ABB, Baden [425, 426]	92	TEM_{00q}	90	10	10	
SPC[a], Lausanne [127, 128, 425, 1289]	90.8	TEM_{00q}	150	15	5	Grating output
	100	TEM_{00q}	90	15	15	
	200 ($2\Omega_c$)	TEM_{00q}	8	3.5	15	
IAP, Nizhny Novgorod [1290]	100	TE_{061}	260	6.5	0.04	Echelette Cavity
MIT, Cambridge [1291–1293]	136	$HE^{0}{}_{061}$	83	18	0.003	Confocal
	114.3	$HE^{0}{}_{051}$	75	16	0.003	Slot-cavity
Moscow-State UNIV	35	TEM_{00q}	1	15	CW	
[1294]	95	TEM_{00q}	1	15	CW	
NRL, Washington D.C. [921, 1295, 1296]	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[b], Otawara	112	TEM_{00q}	100	12	5	
[601]	120	TEM_{00}	26	10 (DEB)	3	
UESTC, Chengdu [1297–1300]	205.7–209.0	TE_{06}	20	11.8	0.1	Confocal cavity
	395.35 ($2\Omega_c$)		6.44	3.4	0.1	Confocal cavity

SDC single-stage depressed collector, *DEB* dual electron beam (1 annular beam, 1 pencil beam)

[a] Swiss Plasma Center, formerly CRPP

[b] Formerly TOSHIBA

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
IAP	31.5–34.5	TE_{11}[a]/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)	Superradiance
IAP	38	$\mathrm{TE}_{11}{}^{*}/\mathrm{TE}_{21}$ ($2\Omega_c$)	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 [1278, 1279, 1301–1310]	125	TE_{41}	10	2	-	0.9	0.5	1.0	Oscillator
LLNL Livermore [1311]	220	TE_{11}	50	2.5	-	3.0	2.0	1.0	Oscillator
MIT Cambridge [1162, 1312, 1313]	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 [1314]	35, 70–90	TE_{61}	0.02	0.002	-	1.0	0.6	0.2 (100)	Oscillator
UNIV. Michigan [1315, 1316]	15	TE_{11}	7	1.5	-	0.45	0.4	1.2	Oscillator
UNIV. Strathclyde [1317–1319]	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

[a] Output mode, HERC Moscow, IAP Nizhny Novgorod, IHCE Tomsk, JINR Dubna

Table 24 State-of-the-art of slow-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 [1320]	9.5	TM_{01}	35	3.5	-	1.15	0.4	2.5	Oscillator Corr. waveguide
Tomsk Polytechn. Inst. [1163]	25		20	0.2	-	0.64	0.9	14	Oscillator Diel. waveguide
UNIV. Niigata, NIFS, UNIV. Maryland [1164]	19.5	TM_{01}	0.2	3.8	-	0.9	0.035	0.15	Oscillator Corr. waveguide
UNIV. Yale, NRL, Washington D.C. [1165]	6.2	TE_{01}	0.02	10	53	0.2	0.05	0.005	Amplifier Diel. waveguide

8 Gyroklystrons, Gyro-TWTs, Gyrotwystrons, Gyro-BWOs, and Other Gyro-Devices

8.1 Weakly Relativistic Pulse Gyroklystrons

Table 25 Weakly relativistic pulse gyroklystron experimental results

Institution	Frequency (GHz)	Mode	No. of cavities	Power (kW)	Efficiency (%)	Gain (dB)	BW (%)	Type
CPI/MPP[a], Palo Alto [20, 478]	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/MPP[a], Litton, NRL, U.M. [552, 1154, 1321–1328]	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 [1329, 1330]	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 [1331–1346]	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

Table 25 (continued)

Institution	Frequency (GHz)	Mode	No. of cavities	Power (kW)	Efficiency (%)	Gain (dB)	BW (%)	Type
	35.2	TE_{02}	2	750 430	24	20	0.63 0.89	TE_{01} input through 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 [483, 1347–1349]	35 ($2\Omega_c$)	TE_{02}	3	212	16	24	0.44	
Kwangwoon Univ., Seoul [1350]	27.85	TE_{01}	5	150	26	50	0.1	
NRL, Washington D.C. [478, 921, 1150–1153, 1351–1362]	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 [483, 1363]	34.9 ($2\Omega_c$)	TE_{01}-TE_{02}	4	250 (5 av.)	24	36	0.4	

8.2 Weakly Relativistic CW Gyroklystrons

Table 26 Weakly relativistic CW gyroklystron experimental results

Institution	Frequency (GHz)	Mode	No. of cavities	Power (kW)	Efficiency (%)	Gain (dB)	BW (%)	Type
CPI/MPP[a], Litton, NRL, U.M	93.8	TE_{01}	4	10.1 av	33.5	32	0.45	(92 kW, 11% duty)
[441, 1150–1154, 1321–1328]	94.2	TE_{01}	5	10.2 av	31	33	0.75	(102 kW, 10% duty)
IAP N. Novgorod [1333]	9.17	TE_{11}	2	0.7	70	22	0.3	
IAP/ISTOK Moscow [1334, 1337, 1338]	91.8	TE_{01}	4	2.5	25	30	0.35	

QOGK quasi-optical gyro-klystron, *SDC* single-stage depressed collector

[a] Communications & Power Industries/Microwave Power Products, formerly VARIAN

8.3 Relativistic Pulse Gyroklystrons

Table 27 Relativistic pulse gyroklystron experimental results

Institution	Frequency (GHz)	Mode output	No. of cavities	Power (MW)	Efficiency (%)	Gain (dB)	BW (%)	Type
IAP, Nizhny Novgorod, Saratov State UNIV. [1364–1375]	30	TE_{53}	2 (TE_{52}/TE_{53})	15	40	30	0.17	Triode gun
	35.4	TE_{52}	3 (TE_{52}/TE_{52}/TE_{53})	12	30	38	0.17	
		TEM_{00}	2 (TE_{71}/TE_{73})	15	33	30	0.14	
UNIV. Maryland [1143–1147, 1376–1389]	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	

8.4 Weakly Relativistic Gyro-TWTs

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

Institution	Frequency (GHz)	Mode	Power (kW)	Efficiency (%)	Gain (dB)	Bandwidth (%)	Type
BVERI, Beijing [483, 1390–1399]	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/MPP[a], Palo Alto [20, 478, 552, 1154–1156, 1328, 1400–1405]	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 [1406]	10 ($2\Omega_C$)	TE_{-21}/TE_{+11}	180				Gridded gun
IAE-CAEP, Mianyang [1407]	7.8	TE_{11}	104	29.2/41.6	32.2	5.1	SDC
IAP, Nizhny Novgorod [1408–1430]	36.3 ($2\Omega_C$) 34.3 ($2\Omega_C$)	TE_{-21}/TE_{+11}	180	27	25	10	Cusp gun with axis-encircl. beam 3 µs
Helical Waveguide Gyro-TWTs							
	96.2 ($2\Omega_C$)	TE_{-21}/TE_{+11} TE_{-21}/TE_{+11}	120 160 (7.7) 3	23 40 (26) SDC 15 (SDC)	20 23 (26) 54	6 7.7 (7.5) 2.3	Longpulse 110 µs 100 µs pulse (CW) CW, 2-tubes cascade
IECAS, Beijing [483, 1431–1433]	16.2 34.5	TE_{11} TE_{01}	130 110	17.8 15.2	41 33	12.3 5	Periodic lossy periodic lossy
MIT, Cambridge [1434–1453]	140	$HE^{()}_{061}$ (q.o.)	30 0.55	12.5 0.4	29 35	1.6 0.9	At 0.875 kW 400 ps modulation pulse
	250	$TE_{03\text{-}}$like	0.045	0.4	38	3.2	PBG, 260 ps pulses

Table 28 (continued)

Institution	Frequency (GHz)	Mode	Power (kW)	Efficiency (%)	Gain (dB)	Bandwidth (%)	Type
NRL, Washington D.C. [478, 1454–1460]	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 Axis-encircling beam
	34.0(35.6)	TE_{01} (TE_{11})	137(70)	17 (17)	47 (60)	3.3 (17)	2-Stage output
UC Los Angeles/Davis [1461–1473]	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 [1167–1169, 1474–1480]	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 [483, 1481–1512]	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

Table 28 (continued)

Institution	Frequency (GHz)	Mode	Power (kW)	Efficiency (%)	Gain (dB)	Bandwidth (%)	Type
	47	TE_{01}	208(111, 50 av.)	22.2 (18.8)	65	8.8	Lossy circuit
	94	TE_{01}	136 (20.54 av.)	22	71	10	Lossy circuit
	95.6	TE_{01}	135	21	55	13	Lossy circuit with uptaper
	216	TE_{01}	34.1 (3.4 av.)	23.2	59.8	3.7 (> 10 kW)	Lossy circuit
UNIV. Kwangwoon [1513]	14.4	$T\,E_{10}$	14.9	18	27	7	Two-stage circuit
UNIV. Strathclyde [1514–1522]	93 ($2\Omega_C$)	TE_{-21}/TE_{+11}	3.4	4.2	37	5.8	Cusp gun with axis-encircling beam
UNIV. Tel Aviv [1523]	7.3	TE_{10}	0.8	12	26		3-Stage output

[a] Communications & Power Industries, formerly VARIAN

8.5 Relativistic Gyro-TWTs

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

Institution	Frequency (GHz)	Mode	Power (MW)	Efficiency (%)	Gain (dB)	Bandwidth (%)	Type
IAP, Nizhny Novgorod	9.4 ($2\Omega_C$)	TE_{-21}/TE_{+11}	1.1	29	37	21	Helical waveguide
UNIV. Strathclyde [741, 1170, 1171, 1408–1410, 1524–1528]							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 [1529]	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.[a] [1530, 1531]	35	TE_{11}	20	11	30		Explosive-emission gun, bifilar helical wiggler
UNIV. Strathclyde [1532–1537]	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

[a] 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

8.6 Weakly Relativistic Pulse Gyrotwystrons

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

Institution	Frequency (GHz)	Mode		Power (kW)	Efficiency (%)	Gain (dB)	BW (%)
		Cavity	TW section				
CPI/MPP[a], Palo Alto [441, 1154, 1156, 1328]	94	TE_{01} (4 cav.)	TE_{01}	59 (5.9 av.)	14.9	35	1.6
NRL, Washington D.C. [1538, 1539]	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. [1540, 1541]	9.2	TE_{01} (2 cav.)	TE_{01}	4.8	14	20	0.9
				4.4	27.5	18	1.6

[a] Communications & Power Industries/Microwave Power Products, formerly VARIAN

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

Institution	Frequency (GHz)	Mode		Power (kW)	Efficiency (%)	Gain (dB)	BW (%)
		Cavity	TW section				
IECAS [1542–1549]	33.1	TE_{01}/coupled cavity ($2\Omega_c$) TE_{02}/TE_{03}	TE_{03} (Ω_c)	75	7.1	25	1.1
Seoul National UNIV. [1550]	33.9	TE_{10}	TE_{10} ($3\Omega_c$)	10^{-4}	2×10^{-3}	LO-gyro-TWT	3.8
UNIV. Maryland. [1205, 1551–1556]	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}

8.8 Relativistic Pulse Gyrotwystrons

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

Institution	Frequency (GHz)	Mode		Power (MW)	Efficiency (%)	Gain (dB)	BW (%)
		Cavity	TW section				
UNIV. Maryland [1389, 1557, 1558]	9.878	TE_{01}	TE_{01}	21.6	21	25.5	
	19.76	TE_{01} (9.88 GHz)	TE_{02} ($2\Omega_c$)	12	11	21	

8.9 Weakly Relativistic Pulse Gyro-BWOs

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

1420–1423	Frequency (GHz)	Mode	Power (kW)	Efficiency (%)	Bandwidth (%)	Type
UNIV. Strathclyde IAP N. Novgorod [1559–1562]	8.6 ($2\Omega_C$)	TE_{+21}/TE_{-11}	65	16.5	17	Quasi-Pierce gun with kicker
IAP, N. Novgorod KIT[a], Karlsruhe [395, 1116, 1411–1417, 1563, 1564]	24.7 ($2\Omega_C$)	TE_{+21}/TE_{-11}	7	15 23 (SDC)	5	MIG CW operation
IAP, Nizhny Novgorod [1414, 1426, 1565]	35–38 ($2\Omega_C$)	TE_{+21}/TE_{-11}	34	7	15	Quasi-Pierce gun with kicker
	35 ($2\Omega_C$)	TE_{+21}/TE_{-11}	10	7	15	Cusp gun with thermal cathode
	96 ($2\Omega_C$)	TE_{+21}/TE_{-11}	1.3		4.2	Cusp gun with thermal cathode Two-tubes cascade
	90–195 (15 bands)	TEM_{00}	0.2–1.2	2–12 (SDC)	74 (70% fill factor)	Zigzag quasi-optical transmission line circuit, Brewster window, CW
IECAS, BVERI, Beijing [1566, 1567]	17.2	TE_{01}	48	10.5 21 (SDC)	5	TE_{10}^{r} output
MIT, Cambridge, LLNL, Livermore [1568]	140	TE_{12}^{c}	2	2	9	
NRL, Washington D.C. [1569]	27.8	TE_{10}^{r}	2	9	3	Electric tuning
	29.2	TE_{10}^{r}	6	15	13	MAGNETIC tuning
NTHU, Hsinchu [1570–1578]	k33.5	TE_{11}^{c}	20–67	6.5–21.7	5	injection locked
			115	23	8.5	Free running
			149	30	4	Electric + magnetic tuning
			154	39	1	Injection locked
			164	41	1	Inverse injec. locked
		TE_{01}^{c}	123	24.5	15.8	Sliced circuit
		TE_{02}^{c}	2.8	22.6	9.5	Sliced circuit
UNIV. Strathclyde [1579–1584]	95 ($2\Omega_C$)	TE_{+21}/TE_{-11}	12	20	15.3	Magnetic tuning, casp gun
UNIV. Utah [1585]	10	TE_{10}^{r}	0.72	10	8	

r rectangular waveguide, *c* circular waveguide

[a] Formerly KfK, then FZK

8.10 Relativistic Pulse Gyro-BWOs

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

Institution	Frequency (GHz)	Mode	Power (MW)	Efficiency (%)	BW (%)	Voltage (MV)	Current (kA)	Type
IAP, N. Novgorod [1586, 1587]	10	TM_{11}	200	22	15 (ΔB)	0.45	2	Cherenkov with cycl. mode selection
	35 (2Ωc)	TE_{-21}/TE_{+11}	1.15	10 axis	encircling	0.35 e-beam	0.032	Helical w.g. with Δm = 3 perturbation
UNIV. Kanazawa [1588, 1589]	9–13	$TE_{10}{}^{r}$	1	0.75 (0.02)	1	0.45	0.3(10)	
UNIV. Michigan [1590, 1591]	4–6	TE_{11}	55 (30)	8 (4.3)	1	0.7	1	
	5–6 (2 Ωc)	TE_{11}	1	0.15	4			
USAF Phillips Lab. Aberdeen [1592, 1593]	4.2	TE_{21}	4	1	1	0.4	1	
	4.4	TE_{01}	0.15	0.04	1	0.4	1	

r rectangular waveguide

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