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State-of-the-Art of High-Power Gyro-Devices and Free Electron Masers

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Abstract

This paper presents a review of the experimental achievements related to the development of high-power gyrotron oscillators for long-pulse or CW operation and pulsed gyrotrons for many applications. In addition, this work gives a short overview on the present development status of frequency step-tunable and multi-frequency gyrotrons, coaxial-cavity multi-megawatt gyrotrons, gyrotrons for technological and spectroscopy applications, relativistic gyrotrons, large orbit gyrotrons (LOGs), quasi-optical gyrotrons, fast- and slow-wave cyclotron autoresonance masers (CARMs), gyroklystrons, gyro-TWT amplifiers, gyrotwystron amplifiers, gyro-BWOs, gyro-harmonic converters, gyro-peniotrons, magnicons, free electron masers (FEMs), 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 resonance heating (ECRH), 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-class gyrotrons employing synthetic diamond output windows is 30 min (CPI and European KIT-SPC-THALES collaboration). The world record parameters of the European tube are as follows: 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 energy recovery. A maximum output power of 1.5 MW in 4.0-s pulses at 45% efficiency was generated with the QST-TOSHIBA (now CANON) 110-GHz gyrotron. The Japan 170-GHz ITER gyrotron achieved 1 MW, 800 s at 55% efficiency and holds the energy world record of 2.88 GJ (0.8 MW, 60 min) and the efficiency record of 57% for tubes with an output power of more than 0.5 MW. The Russian 170-GHz ITER gyrotron obtained 0.99 (1.2) MW with a pulse duration of 1000 (100) s and 53% efficiency. The prototype tube of the European 2-MW, 170-GHz coaxial-cavity gyrotron achieved in short pulses the record power of 2.2 MW at 48% efficiency and 96% Gaussian mode purity. Gyrotrons with pulsed magnet for various short-pulse applications

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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 ($\eta = 0.6\%$). 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, $\eta \geq 30\%$. The CW powers produced by gyroklystrons and FEMs are 10 kW (94 GHz) and 36 W (15 GHz), respectively. The IR FEL at the Thomas Jefferson National Accelerator Facility in the USA obtained a record average power of 14.2 kW at a wavelength of 1.6 μm. The THz FEL (NOVEL) at the Budker Institute of Nuclear Physics in Russia achieved a maximum average power of 0.5 kW at wavelengths 50–240 μm (6.00–1.25 THz).

Keywords Electron cyclotron maser · Gyrotron · Quasi-optical gyrotron · Gyroklystron · Gyro-travelling-wave amplifier · Gyrotwystron amplifier · Gyro-backward-wave oscillator · Cyclotron autoresonance maser · Gyro-peniotron · Magnicon · Free electron maser · Dielectric vacuum windows

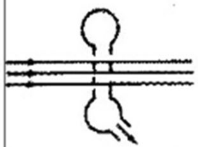
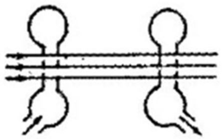
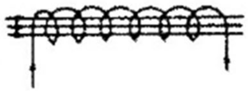
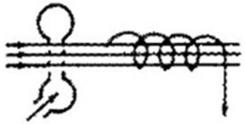
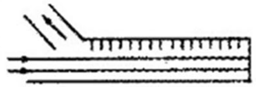
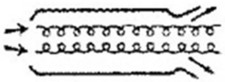
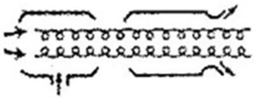
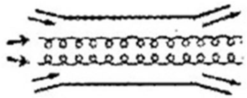
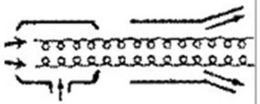
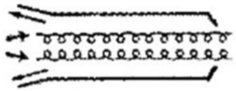
1 Introduction

The possible applications of gyrotron oscillators (gyromonotrons, or just gyrotrons) and other electron cyclotron maser (ECM) fast-wave devices (Table 1) span a wide range of technologies [1–7] . 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 1–8 GHz), electron cyclotron resonance heating and non-inductive electron cyclotron current drive (ECRH&CD 28–170 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 work on ECM devices has investigated the conventional gyrotron [8–29] in which the wave vector of the radiation in an open-ended, irregular cylindrical waveguide cavity is almost transverse to the direction of the applied magnetic field, generating 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 0.1–1.0 MW at frequencies between 28 and 170 GHz have been used very successfully in thermonuclear fusion research for plasma ionization and start-up, ECRH, and local current density profile control by ECCD at system power levels up to 10 MW.

ECRH has become a well-established heating method for both tokamaks [30–60] and stellarators [59–83]. 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 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 future tokamak experiment ITER (International Thermonuclear Experimental Reactor) and of the new stellarator (W7-X) at the Max-Planck-Institut für Plasmaphysik in Greifswald are between 10 and 40 MW at frequencies between 140 GHz

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

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

and 170 GHz [22, 25–28, 37, 50, 60–78, 84–99]. This suggests that mm-wave gyrotrons that generate output power of at least 1 MW, CW, per tube are required. Since efficient ECRH 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 TEM_{00} fundamental Gaussian beam mode. Single-mode 110–170 GHz gyromonotrons with conventional cylindrical cavity, capable of 1.5 MW per tube, CW [22–28], and 2 MW coaxial-cavity gyrotrons [90–100] 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 [25–28, 37, 92–104]. Frequency tuning has been shown to be possible on quasi-optical Fabry-Perot cavity gyrotrons [105, 106] as well as on cylindrical cavity gyrotrons by frequency tuning in steps (different operating cavity modes) [107–142].

This review reports on the present status and future prospects of gyrotrons and RF vacuum windows for ECRH&CD in fusion plasmas and for ECR plasma sources for generation of multi-charged ions and soft X-rays [143–165] (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 [166–219], 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) [220–305], remote detection of concealed radioactive materials [306–309], wireless communication [310], and medical applications [311–316] (Tables 14, 15, 16, 17 and 18) and of quasi-optical gyrotrons (Table 22). Gyrotrons also are successfully utilized in materials processing (e.g., advanced ceramic sintering, surface hardening or dielectric coating of metals and alloys, semiconductor production, penetrating rocks) as well as in plasma chemistry [1–7, 317–337]. 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 [338] and Gycom in Russia [324, 332–335, 339–344] 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 [345–347]. 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 [348–360]. 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, 26, and 27), gyrotron travelling wave tube (Gyro-TWT) amplifiers (Tables 28 and 29), gyrotwystrons (Tables 30, 31, and 32), peniotrons and gyropeniotrons (Tables 35 and 36) and magnicons (Table 37) for such purposes as well as of free electron masers (FEM) (Table 38) and broadband gyrotron backward wave oscillators (Gyro-BWO) (Tables 33 and 34) for use as drivers for FEM amplifiers.

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			
ABB, Baden [382, 451]	8	TE_{01}	TE_{01}	0.35	35	0.5
	39	TE_{02}	TE_{02}	0.25	42	0.1
ARIEL UNIV., Ariel [452–455]	27, 31, 39	TE_{11}, TE_{21}, TE_{01}	TE_{11}, TE_{21}, TE_{01}	0.004–0.006	11	0.0000002
	95.2	TE_{02}	TE_{02}	0.010	14	10
CPI1), Palo Alto [14, 19, 456–473]	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	$TE_{10,3}$	TEM_{00}	0.6	47 (SDC)	2.25
	84	$TE_{15,2}$	$TE_{15,2/4}$	0.5 (0.9)	28	0.1 (0.001)
	84	$TE_{15,4}$	TEM_{00}	0.56	44 (SDC)	2.0
	94.9	$TE_{6,2}$	TEM_{00}	0.12	50 (SDC)	CW
	95.3	$TE_{22,6}$	TEM_{00}	1.4 (1.92)	51 (40) (SDC)	5 (0.005)
CPI1), NIFS Palo Alto, Toki [79, 80, 457–461, 474–477]	84	$TE_{15,3}$	TEM_{00}	0.5 (0.4)	29	2.0 (10.5)
				0.1	14	CW
				0.59(0.25)	41 (32) (SDC)	0.001 (0.2)
GYCOM, IAP Nizhny Novgorod [15, 108, 109, 127–134, 478–494]	5	TE_{01}	TE_{01}	0.23	26	0.1
	25 ($2\Omega_c$)	TE_{03}	TE_{03}	0.8/0.87	40/25(2e-beams)	0.0001
	28	$TE_{4,2}/TE_{6,2}$	TEM_{00}	0.5	36	0.5
	37.5	TE_{62}	TEM_{00}	0.5	35	0.1
	44.8	$TE_{15,1}$	$TE_{15,1}$	1.25	35	0.0001
	53.2,54.5	TE_{83}	TEM_{00}	0.5 (0.3)	40 (36)	0.1 (1.0)
	53.5 ($3\Omega_c$)	$TE_{7,1/7,2}$	TE_{72}	0.15	10	0.00004
	68 (70)	TE_{93}	TEM_{00}	0.5 (0.68)	50 (48) (SDC)	1.0 (3.0)
	75	$TE_{9,4}$ /$TE_{11,5}$	TEM_{00}	0.5/0.8	37/70 (SDC)	0.1
	82.5	$TE_{11,3}$	$TE_{11,3}$	1.0 (1.5)	50 (36)	0.0001
	82.7	$TE_{10,4}$	TEM_{00}	0.65 (0.2)	53 (SDC)	3.0 (CW)
	84	$TE_{12,5}$	TEM_{00}	0.88 (0.2)	54 (50) (SDC)	3.0 (CW)
Low-Q cavity tunable	64–91	Echelette	Mode	80–200	11–30	0.0001
HUGHES, Torrance [379]	60	TE_{02}	TE_{02}	0.2	35	0.1
IECAS, Beijing [495–498]	24.1	TE_{01}	TE_{01}	0.15	24	0.02
	34.3 ($2\Omega_c$)	$TE_{02/03}$	TE_{03}	0.2	30	0.02
	94	TE_{02}	TE_{02}	0.0158	30.3	120

Table 2 (continued)

Institution	Frequency [GHz]	Mode		Power [MW]	Efficiency [%]	Pulse length [s]
		Cavity	Output			
IECAS, NTHU [499, 500]	94	TE_{01}	TE_{01}	0.008	9.5	0.1
IAE-CAEP, Mianyang [501–503]	95	TE_{03}/TE_{62}	TE_{03}/TEM_{00}	0.020/0.030	20	10/600
	95 ($2\Omega_c$)/95 ($3\Omega_c$)	TE_{02}/TE_{61}	TE_{02}/TE_{61}	0.012/0.006	9.9/4	0.03/0.0001
LAP/INPE, Sao Paulo [504]	24.2	TE_{12}	TE_{12}	0.0058	16	0.000015
	30.4	TE_{22}	TE_{22}	0.0063	18.5	0.000015
MITSUBISHI, Amagasaki KYOTO UNIV. [505]	88	$TE_{8,2}$	TEM_{00}	0.35	29	0.1
NEC, Kawasaki [506]	35	TE_{01}	TE_{01}	0.1	30	0.001
NRL, Washington D.C. [379, 507–509]	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 [510]	70	TE_{02}	TE_{02}	0.21 (0.14)	38 (30)	0.1 (CW)
SPbSTU, St. Petersburg KIT[3)] Karlsruhe [511–518]	74.2	$TE_{12,3}$	$TE_{12,3}$	0.1	44	0.00005
THALES ED[4)], Velizy [382, 519]	8	$TE_{5,1}$	$TE_{5,1}$	1.0	45	1.0
	35	TE_{02}	TE_{02}	0.335	43	0.15
TSUKUBA UNIV., CANON[5)]	28	TE_{02}	TE_{02}	0.2	35.7	0.075
Ibaraki, Otawara [82, 83, 520–532]	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
UESTC, Chengdu [533–540]	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_{61}/TE_{62}	0.027	30	CW
			TEM_{00}	0.02	45 (SDC)	CW
UNIV. FUKUI, TOSHIBA [506]	70	TE_{02}	TE_{02}	0.025	28.4	0.001
UNIST, Ulsan [541]	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 3 Present development status of high-frequency gyrotron oscillators for ECRH and stability control in magnetic fusion devices (100 GHz ≤ f < 140 GHz, $\tau \geq 0.1$ ms)

Institution	Frequency [GHz]	Mode		Power [MW]	Efficiency [%]	Pulse length [s]
		Cavity	Output			
CPI[1)], Palo Alto [14, 53, 457–461, 470–473, 542–566]	106.4 ($2\Omega_c$)	$TE_{02/03}$	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
				0.95/0.55	34 (SDC)	5.0/10.0
KIT[2)], Karlsruhe [110–116, 567–586]	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 [15, 384, 484, 587–596]	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 [15, 108, 109, 123–142, 480–485, 597–601]	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 [22, 532, 602–629]	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	48 (SDC)	3.3
				0.35	48 (SDC)	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	24	0.1
				0.25	24	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
MITSUBISHI, Amagasaki [630, 631]	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)], Velizy [382, 519]	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 [632–642]	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 4 Present development status of high-frequency gyrotron oscillators for ECRH and stability control in magnetic fusion devices ($f \geq 140$ GHz, $\tau \geq 0.1$ ms)

Institution	Frequency [GHz]	Mode		Power [MW]	Efficiency [%]	Pulse length [s]
		Cavity	Output			
BVERI, Beijing [643]	140.2	$TE_{22,6}$	$TEM_{00}(TE_{22,6})$	0.56(0.43)	24.5(22.6)	0.001
CPI[1)], Palo Alto [14, 19, 457–461,	140	$TE_{02/03}$	TE_{03}	0.1	27	CW
470, 472, 473, 551–555,	140	$TE_{15,2}$	$TE_{15,2}$	1.04(0.32)	38(31)	0.0005(3.6)
558–566, 617–649]				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 [650]	140	$TE_{7,3}$	TEM_{00}	0.030/0.052	34/39.4 (SDC)	60/30
KIT[2)], PHILIPS[3)] [382, 651]	140.8	TE_{03}	TE_{03}	0.12	26	0.4
KIT[2)], Karlsruhe [110–116, 383,	140.2	$TE_{10,4}$	$TE_{10,4}$	0.69	28	0.005
567–586, 651–667]	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	0.007
				1.48	50 (SDC)	0.007
KIT[2)], SPC[4)], THALES ED[5)], CEA [6,	139.8	$TE_{28,8}$	TEM_{00}	1.0	50/41 (SDC)	12/360
7, 66–78, 90–99, 635, 667–707]				0.92	44 (SDC)	1800
EGYC[6)] [708–717]	170	$TE_{32,9}$	TEM_{00}	1.0	34	0.001
				0.8	37 (SDC)	180
GYCOM, IAP Nizhny Novgorod [15,	140	$TE_{22,6}$	TEM_{00}	0.96	36	1.2
123–142, 411, 481–485, 589–596,				0.54	36	3.0
601, 718–756]				0.26 (0.1)	36	10 (80)
		Dual-team 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)	10/300/1000
	170	$TE_{28,7}$	TEM_{00}	1.0	32.5	0.0001
	170	$TE_{25,10}$	TEM_{00}	1.2/0.96	53/58 (SDC)	100/1000

Table 4 (continued)

Institution	Frequency [GHz]	Mode: Cavity	Mode: Output	Power [MW]	Efficiency [%]	Pulse length [s]	
	170	$TE_{28,12}$	TEM_{00}	1.75/1.5/1.0/0.75	53/47 (SDC)	0.1/2.3/112/500	
	250	$TE_{19,8}$	TEM_{00}	330	30	0.000045	
GYCOM-N, IAP Nizhny Novgorod	140	$TE_{22,6}$	TEM_{00}	0.8	32	0.8	
[15, 108, 109, 480–482, 485, 489,				0.88	50.5 (SDC)	1.0	
594–597, 599, 600, 718, 733, 758]				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	
QST[7], CANON[8] Naka, Otawara	170	$TE_{22,6}$	TEM_{00}	0.45	19	0.05	
[22, 608–625, 759–801]				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] [532, 802–805]	300	$TE_{32,18}$	$TE_{32,18}$	0.52/0.62	20	0.002/0.001	tilted SiO_2 window
NIFS, TSUKUBA UNIV.,CANON[8]	154	$TE_{28,8}$	TEM_{00}	1.25	37 (SDC)	0.004	
Toki, Ibaraki, Otawara [79–82, 477,				0.35	39 (SDC)	1800	
528, 530–532, 806–808]	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 is a collaboration among SPC, Switzerland; KIT, Germany; HELLAS, Greece; CNR, Italy; ENEA Italy, [7] formerly JAERI, then JAEA, [8] formerly TOSHIBA

Table 5 Present experimental development status of short-pulse (3 μs–15 ms) coaxial cavity gyrotron oscillators

Institution	**Frequency** [GHz]	Mode		Power [MW]	**Efficiency** [%]	Corrug. Cavity	
		Cavity	Output			Inner	Outer
KIT[1)] Karlsruhe [6, 22, 25–28, 89–100, 662–668, 684, 809–829]	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*
			TEM_{00}	0.95	20	Yes	No
Pulse length ≤ 100 ms				0.95 (dual beam output)	29 (SDC)	Yes	No
	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 (single-beam output)	28	Yes	No
				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)] [830–863]	170	$TE_{34,19}$	TEM_{00}	2.2	33	Yes	No
				2.1	48 (SDC)	Yes	No
IAP, Nizhny Novgorod [13, 15, 460, 481, 864–872]	45	$TE_{15,1}$	$TE_{15,1}$	1.25	43	No	No
	100	$TE_{21,18}$	$TE_{21,18}$	1.0	35	Yes	No
Pulse length ≤ 0.1 ms				0.5	20	No	No
	100	$TE_{20,13}$	$TE_{20,13}$	2.1	30	No	No
				1.6	38	No	No
	103	$TE_{22,13}$	$TE_{22,13}$	1.0	40	Yes	Yes
				0.7	30	Yes	No
				0.3	14	No	No
	107	$TE_{17,7}$	$TE_{17,7}$	0.7	25	No	No
	110	$TE_{20,13}$	$TE_{20,13}$	1.15	35	Yes	No
	110	$TE_{21,13}$	$TE_{21,13}$	1.0	35	Yes	No
	140	$TE_{28,16}$	$TE_{28,16}$	1.5	33.5	Yes	No *
				1.15	50 (SDC)	Yes	No
			$TE_{76,2}$	1.17	35.2	Yes	Yes
			TEM_{00}	1.1 (dual-beam output)	30	Yes	No
	224 ($2\Omega_c$)	$TE_{33,8}$	$TE_{33,8}$	0.1	11	Yes	No
IAP, KIT[1)] Karlsruhe [809]	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 [873–875]	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 [876]	110/220 ($2\Omega_c$) two electron beams	TE_{02}/TE_{04}	TEM_{00}	0.02	5	No	No

[1)] Formerly KfK, then FZK, * very similar cavity and tube design

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

2 Classification of Fast-Wave Microwave Sources

Fast-wave devices in which the phase velocity v_{ph} of the EM wave is higher than the speed of light c, generate or amplify coherent EM radiation by stimulated emission of bremsstrahlung from a beam of relativistic electrons. The electrons radiate because they undergo oscillations transverse to the direction of beam motion by the action of an external force (field). For such waves, the electric RF field is mainly transverse to the propagation direction.

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[1)], Palo Alto [26, 456–473, 546–555,	8	TE_{21}	TE_{10}	0.4	26.6	0.0005
558–566, 644–649]	(dual rectangular waveguide output)			0.4	34.2 (SDC)	0.0005
	70.15	$TE_{10,3}$	TEM_{00}	0.6	47 (SDC)	2.25
	94.9	TE_{62}	TEM_{00}	0.12	50 (SDC)	CW
	95.3	$TE_{22,6}$	TEM_{00}	0.62 (1.92)	41(40) (SDC)	15 (0.005)
	110	$TE_{22,6}$	TEM_{00}	1.28	42.3 (SDC)	0.001
				0.52	29 (SDC)	10
	140.2	$TE_{27,8}$	TEM_{00}	0.92/0.9	36/33 (SDC)	0.003/1800
AE-CAEP, Mianyang [650]	140	$TE_{7,3}$	TEM_{00}	0.030/0.052	34/39.4 (SDC)	60/30
CPI[1)], NIFS Palo Alto, Toki [79–82, 462]	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 [23, 110–117, 567–586,	117.9	$TE_{19,5}$	TEM_{00}	1.55	49.5 (SDC)	0.007
657–668]	140.2	$TE_{10,4}$	TEM_{00}	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
	162.3	$TE_{25,7}$	TEM_{00}	1.48	50 (SDC)	0.007
KIT[2)], SPC[3)], EGYC, THALES ED[4)], CEA	139.8	$TE_{28,8}$	TEM_{00}	1.0	50 (SDC)	12
[6, 26, 66–70, 89–99, 635, 668–717]				0.92	44 (SDC)	1800
	170	$TE_{32,9}$	TEM_{00}	0.8	37 (SDC)	180
GYCOM, IAP Nizhny Novgorod [482–484,	68 (70)	$TE_{9,3}$	TEM_{00}	0.5 (0.68)	50 (48) (SDC)	1.0 (3.0)
487–490, 590, 591, 596, 598]	75	$TE_{11,5}$	TEM_{00}	0.8	70 (SDC)	0.1
	82.7	$TE_{10,4}$	TEM_{00}	0.65	38	3.0
				0.65	53 (SDC)	0.03
				0.2	52 (SDC)	CW
	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	32	0.8
				0.88	50.5 (SDC)	1.0
	140	$TE_{22,10}$	TEM_{00}	0.99	47 (SDC)	0.5

Table 6 (continued)

Institution	Frequency[GHz]	Mode		Power [MW]	Efficiency [%]	Pulse length [s]
		Cavity	Output			
GYCOM, IAP Nizhny Novgorod [26, 123–142, 489, 718–754]	140	$TE_{22,8}$	TEM_{00}	1.7	42	0.0001
				1.14/0.95/0.7	59/52/49 (SDC)	10/300/1000
	170	$TE_{25,10}$	TEM_{00}	1.2	53 (SDC)	100
				0.96	58 (SDC)	1000
	170	$TE_{28,12}$	TEM_{00}	1.75/1.5/1/0.75	53/47 (SDC)	0.1/2.5/112/500
NRL, Washington D.C. [881]	115	QOG	TEM_{00}	0.43	12.7 (SDC)	10^{-5}
				0.20	16.1 (SDC)	10^{-5}
QST[5)], CANON[6)] Naka, Otawara [602–629, 759–801]	110	$TE_{22,2}$	TEM_{00}	0.61	50 (SDC)	0.05
				0.35	48 (SDC)	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
	138	$TE_{27,10}$	TEM_{00}	1.0	43 (SDC)	100
	170	$TE_{22,6}$	TEM_{00}	0.25	19/32 (SDC)	0.4
	170.2	$TE_{31,8}$	TEM_{00}	1.2	57 (SDC)	0.003
				1.0	55 (SDC)	800
				0.8	57 (SDC)	3600
	170	$TE_{31,11}$	TEM_{00}	1.23/1.05/0.6	47/51/46 SDC	2.0/300/1000
NIFS, TSUKUBA UNIV., CANON[6)] Toki, Ibaraki, Otawara [79–83, 477, 523–532, 806–808]	77	$TE_{18,6}$	TEM_{00}	1.9	38 (SDC)	0.1
				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	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 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

Institution	Frequency **[GHz]**	Mode		Power [MW]	Efficiency [%]	Pulse length [s]	
		Cavity	Output				
KIT[1)], Karlsruhe [26, 110–122, 572, 581–586]	114.2	$TE_{18,5}$	TEM_{00}	0.85	23	0.001	
	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	
GYCOM, IAP Nizhny Novgorod [26, 108, 109, 123–142, 484, 486–489, 596, 882]	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	

Table 7 (continued)

Institution	Frequency **[GHz]**	Mode		Power [MW]	Efficiency [%]	Pulse length [s]	
		Cavity	Output				
	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 [26, 781, 883]	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 [804, 805]	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 [884–893]	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 8 Multi-frequency gyrotrons operating at different transmission maxima of a plane single-disk window

Institution	**Frequency** [GHz]	Mode		Power [MW]	Efficiency [%]	Pulse length [s]	No. of frequencies
		Cavity	Output				
CPI, Palo Alto [566]	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)]	84	$TE_{17,5}$	TEM_{00}	0.97	31	1.1	2f-Gyrotron
[26, 690, 894]	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	121.5	$TE_{20,5}$	TEM_{00}	0.5	30	0.1	3f-Gyrotron
[26, 42–48, 57, 125–142, 485, 489,	140.0	$TE_{22,6}$	TEM_{00}	0.5	30	0.5	3f-Gyrotron
596, 598–601, 740–754, 882]	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
QST[5)], CANON[6)] Naka, Otawara	104	$TE_{19,7}$	TEM_{00}	1.0/0.93/0.3	41 (SDC)	2/5/20	4f-Gyrotron
[26, 781, 784, 786–801, 804, 883, 895]	136.8	$TE_{25,9}$	TEM_{00}	1.0/0.3	42 (SDC)	6/250	4f-Gyrotron
	170	$TE_{31,11}$	TEM_{00}	1.2/1.0/0.6	47/49/46 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	82	$TE_{17,6}$	TEM_{00}	1.0/0.4	35 (SDC)	1/2	3f-Gyrotron
[624–629, 896]	110	$TE_{22,8}$	TEM_{00}	1.9/1.5/1.0	47/45 (SDC)	1/3.8/100	3f-Gyrotron
	137.6	$TE_{27,10}$	TEM_{00}	1.3/1.0	43 (SDC)	1/100	3f-Gyrotron
NIFS, TSUKUBA UNIV., CANON[6)]	28.04	$TE_{8,5}$	TEM_{00}	1.65	31	0.002	2f-Gyrotron
Toki, Ibaraki, Otawara [532, 804–808, 897]	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 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

Institution	Frequency [GHz]	Mode		Power [MW]	Efficiency [%]	Pulse length [s]
		Cavity	Output			
IAP, Nizhny Novgorod [13, 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 [115, 818–821, 823–825]	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)] [849–853, 856, 859]	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

The condition for coherent radiation is that the contributions of different electrons reinforce the originally emitted radiation in oscillators or the incident EM wave in amplifiers. This condition is satisfied if a bunching mechanism exists to create electron density variations of a size comparable to the wavelength of the imposed EM wave. To achieve such a mechanism, a resonance condition must be satisfied between the periodic motion of the electrons and the EM wave in the interaction region [18, 21, 27, 361]

$$\omega - k_z v_z \cong s\Omega \quad , \quad s = 1, 2, \ldots \quad (k_z v_z = \text{Doppler term}), \tag{1}$$

where ω and k_z are the wave angular frequency and characteristic axial wavenumber, respectively, v_z is the translational electron drift velocity, Ω is an effective frequency, which is associated with macroscopic oscillatory motion of the electrons, and s is the harmonic number.

In ECMs, EM energy is radiated by relativistic electrons gyrating in an external longitudinal magnetic field. In this case, the effective frequency Ω corresponds to the relativistic electron cyclotron frequency:

$$\Omega_c = \Omega_{co}/\gamma \quad \text{with} \quad \Omega_{co} = eB_o/m_o \quad \text{and} \quad \gamma = \left[1-(v/c)^2\right]^{-1/2} \approx 1 + eV_o/m_o c^2$$
$$= 1 + eV_o/511 \tag{2}$$

Table 10 Experimental parameters of high-power millimeter-wave vacuum windows [15, 19, 22, 26–28, 127–142, 382–384, 458–472, 477, 484, 489, 490, 524–532, 542–649, 669–805, 882, 883, 895–944]

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	IAP/GYCOM
		960	140	1.2	IAP/GYCOM
		550	140	3.0	IAP/GYCOM
		100	140	80	IAP/GYCOM
		1030	170	1.0	IAP/GYCOM
		500	170	5.0	IAP/GYCOM
		270	170	10	IAP/GYCOM
Silicon nitride	Single-disk gas face and water edge cooled	130	84	30.0	NIFS/CPI
		520	168	1.0	NIFS/CANON[1)]
Sapphire	Single-disk LN_2 edge cooled	530	118	5.0	CEA/SPC/KIT/THALES
		350	118	100	CEA/SPC/KIT/THALES
		285*	140	3.0	IAP/INFK
		500	140	0.5	KIT/IAP/IGVP/IPP
		370	140	1.3	KIT/IAP/IGVP/IPP
Sapphire	Single-disk LHe edge cooled	410	110	1.0	QST/CANON[1)]
		500	110	0.5	QST/GA
Sapphire	Double-disk FC75 face cooled	200	28	CW	CPI
		200	35	CW	CPI
		200	60	CW	CPI
		400	84	10.5	NIFS/CPI
		350	110	5.0	QST/CANON[1)]
		200	140	CW	CPI
		500	170	0.6	QST/CANON[1)]
Sapphire	Distributed water cooled	65**	110	0.3	GA/QST
		200*	110	0.7	GA/CPI
Au-doped silicon	Single-disk CO_2 gas edge cooled	600	140	0.8	IAP/GYCOM
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

Table 10 (continued)

Material	Type	Power (kW)	Frequency (GHz)	Pulse length (s)	Institution
		1000	170	1000	IAP/GYCOM
		1000	170	800	QST/CANON[1)]
		800	170	3600	QST/CANON[1)]
		600	203	10	QST/CANON[1)]

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

[1)] Formerly TOSHIBA

where $-e$ and m_o are the charge and rest mass of an electron, γ is the relativistic Lorentz factor, B_o is the magnitude of the external magnetic field, and eV_o is the energy of the accelerated electrons in keV. Here, V_o is the acceleration voltage. The nonrelativistic electron cyclotron frequency is given by the formula f_{co} (GHz) = $28B_o$(T). A group of relativistic electrons gyrating in a strong magnetic field will radiate coherently due to bunching caused by the relativistic mass dependence of their gyration frequency. Bunching is achieved because, as an electron loses energy, its relativistic mass decreases and it thus gyrates faster. The consequence is that a small amplitude wave's electric field, while extracting energy from the particles, causes them to become bunched in the gyration phase and reinforces the existing wave electric field. The strength of the magnetic field determines the radiation frequency.

In the case of a spatially periodic magnetic or electric field (undulator/wiggler), the transverse oscillation frequency $\Omega = \Omega_b$ (bounce frequency) of the moving charges is proportional to the ratio of the electron beam velocity v_z to the spatial period λ_w of the wiggler field. Thus,

$$\Omega_b = k_w v_z \quad , \qquad k_w = 2\pi/\lambda_w \tag{3}$$

The operating frequency of such devices, an example of which is the free electron maser (FEM) [362–368], is determined by the condition that an electron in its rest frame "observes" both the radiation and the periodic external force at the same frequency. If the electron beam is highly relativistic ($v_{ph} \cong v_z \cong c$), the radiation will have a much shorter wavelength than the external force in the laboratory frame ($\lambda \cong \lambda_w/2\gamma^2$, so that $\omega \cong 2\gamma^2\,\Omega_b$). Therefore, FEMs are capable of generating EM waves of very short wavelength determined by the relativistic Doppler effect. Bunching of electrons in FEMs is due to the perturbation of the beam electrons by the ponderomotive potential well, which is caused by "beating" of the EM wave with the spatially periodic wiggler field. It is this bunching that enforces the coherence of the emitted radiation.

In the case of the ECMs and FEMs, unlike most conventional microwave sources and lasers, the radiation wavelength is not determined by the characteristic size of the interaction region. Such fast-wave devices require no slow-wave structure (e.g., periodically rippled walls or dielectric loading) and can instead use a simple hollow-pipe oversized waveguide as interaction circuit. These devices are capable of producing very high-power radiation at cm-, mm-, and sub-millimeter wavelengths since the use of large waveguide or cavity cross sections reduces Ohmic wall losses and breakdown restrictions, as well as permitting the passage of larger, higher-power electron beams. It also relaxes the constraint that the electron beam in a single cavity can only remain in a favorable RF phase for half of a RF period (as in klystrons and other devices employing

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) [86, 102, 919, 925, 932, 934, 942, 945–950]

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 k [W/mK]	300 K	260	55	59	40	150	2000	330
	500 K				6		1100	
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) tanδ [10^{-5}]		70	115	30	20	0.35	2	7
Metallizing and brazing		o.k.	o.k.	o.k.	o.k.	o.k	o.k.	o.k.
Bakeout temperature				550 °C	550 °C	550 °C	450 °C	550 °C
Possible size ∅ [mm]		150	145	300	270	127	120	
Cost		Medium	Medium	High	High	Low	Very high	Medium
Failure resistance R' $R' = k\sigma_B (1-\nu)/E\alpha$		10.3	15.7	44.5	6.0	284	772	40
RF-power capacity P_T $P_T = R'\rho c_P/((1+\varepsilon_r')\tan\delta)$		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 LN_2-temperature—77 K (LNe-temperature—30 K) (p.c. = poly-crystalline, s.c. = single-crystalline) [919]

Material	Sapphire (Al_2O_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 (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) tanδ [10^{-5}]	0.57 (0.2)	0.35	2
Metallizing and brazing	o.k.	o.k	o.k.
Bakeout temperature	550 °C	550 °C	450 °C
Possible size ∅ [mm]	270	127	160
Cost	High	Low	Very high
Failure Resistance R' $R' = k\sigma_B (1-\nu)/E\alpha$	130 (2871)	2463	3214
RF-power capacity P_T $P_T = R'\rho\, c_P/((1+\varepsilon_r')\tan\delta)$	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

transition radiation). In contrast with klystrons, the reference phase for the waves in fast-wave devices is the phase of the electron oscillations. Therefore, the departure from the synchronous condition, which is given by the transit angle $\theta = (\omega\text{-}k_z v_z\text{-}s\Omega)L/v_z$, where L

Table 13 Options for 1 MW, CW, 170 GHz gyrotron windows [84–89, 102, 919]

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

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

Table 14 Performance parameters of mm- and submillimeter-wave gyrotrons operating at the 2nd harmonic of the electron cyclotron frequency, with output power $\geq$ 1 kW

Institution	Frequency [GHz]	Mode	Power [kW]	Efficiency [%]	Pulse length [ms]
CPI[1)], Palo Alto [954] IAP, N. Novgorod [166, 167, 955]	250	$TE_{11,1}/TE_{11,2}$	10	3.4	0.1
	157	TE_{03}	2.4	9.5	CW
	250	TE_{02}	4.3	18	CW
	250	TE_{65}	1	5	CW
	326	TE_{23}	1.5	6.2	CW
MIT, Cambridge [956–958]	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	$TE_{15,2}$	7	2	0.0015
	467	$TE_{12,3}$	22	3.5	0.0015
	503	$TE_{17,2}$	10	5.5	0.0015
UESTC, Chengdu [959–965]	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)
					0.004
UNIVERSITY, Fukui [182–195, 197–202, 966–978]	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

is the interaction length, can now be of order 2π or less, even in cavities or waveguides that are many wavelengths long [369].

3 Dispersion Diagrams of Fast Cyclotron Mode Interaction

The origin of the ECMs traces back to the late 1950s, when three investigators began to examine theoretically the generation of microwaves by the ECM interaction [8, 9, 27]: Richard Twiss in Australia [370], Jürgen Schneider in the USA [371], and Andrei Gaponov in Russia [372]. A short note on the possibility to use the rotational energy of a helical electron beam for microwave generation was published by Hans Kleinwächter in 1950 [373]. In early experiments with devices of this type, there was some debate about the generation mechanism and the relative roles of fast-wave interactions mainly producing azimuthal electron bunching and slow-wave interactions mainly producing axial bunching [8, 9, 27, 374, 375]. The predominance of the fast-wave ECM resonance with its azimuthal bunching in producing microwaves was experimentally verified in the mid-1960s in the USA [376] (where the term “electron cyclotron maser” was apparently coined) and in Russia [377].

Table 15 Operation results of high harmonic gyrotrons with axis-encircling electron beam (LOG) and permanent magnet (Nd Fe B) at the 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 [979–984]	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 [173–181, 985–991]	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

Many configurations can be used to produce coherent radiation based on the ECM instability. The departure point for designs based on a particular concept is the wave-particle interaction. Dispersion diagrams, also called ω-k_z plots or Brillouin diagrams [378–384], show the region of cyclotron interaction (maximum gain of the instability) between an EM mode and a fast electron cyclotron mode (fundamental or harmonic) as an intersection of the waveguide mode dispersion curve (hyperbola):

$$\omega^2 = {k_z}^2 c^2 + {k_\perp}^2 c^2 \tag{4}$$

with the beam-wave resonance line (straight) given by eq. (1). In the case of a device with cylindrical resonator the perpendicular wavenumber is given by $k_\perp = X_{mn}/R_o$ where X_{mn} is the nth root of the corresponding Bessel function (TM_{mn} modes) or derivative (TE_{mn} modes) and R_o is the waveguide radius. Phase velocity synchronism of the two waves is given in the intersection region. The interaction can result in a device that is either an oscillator or an amplifier. In the following subsections, the different ECM devices are classified according to their dispersion diagrams.

3.1 Gyrotron Oscillator and Gyroklystron Amplifier

Gyrotron oscillators were the first ECMs to undergo major development [27]. In autumn 1964 scientists at Institute of Applied Physics (IAP) in Nizhny Novgorod, Russia, operated the first gyrotron (TE_{101} mode in rectangular cavity, power: 6 W, CW) [18]. In 1966 the term “gyrotron” was coined by Arcady Goldenberg from IAP. Increases in device power were the result of Russian developments from the early 1970s in magnetron injection guns (MIGs), which produce electron beams with the necessary transverse energy (while minimizing the spread in transverse velocities) and in tapered, open-ended waveguide cavities that maximize the interaction efficiency by

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

Institution	Frequency [GHz]	Mode	Power [MW]	Efficiency [%]	Pulse length [μs]	
IAP, Nizhny Novgorod [166–172, 174–181, 296, 306, 307]	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	
	670	$TE_{31,8}$	0.21	20	20	
	1002	TE_{68}	0.0018	2.4	40	
	1024	$TE_{17,4}$	0.005	6.1	40	
	1300	$TE_{24,4}$	0.0005	0.6	40	
	263.2	$TE_{5,3}$	0.001	17	CW	CW operation
MIT, Cambridge [107, 874, 884–893, 992–1005]	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	
	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 [961, 1006, 1007]	201.5	TE_{23}	0.015	6.0	4	500 mW with cold cathode
	216.4	TE_{23}	0.032	12.5	4	
	221	TE_{03}	0.045 (0.012)	17.3 (4.4)	4	
	228.6	TE_{52}	0.025	14.9	4	
UNIVERSITY, Fukui [16, 200, 203–215, 967–970, 1008]	202.9	TE_{33}	0.001	10	10000	
	278	TE_{33}	0.001	5	1000	TEM_{00} output mode
	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	

tailoring the electric field distribution in the resonator [8–17]. In 1967, Igor Antakov performed at IAP first gyroklystron amplifier experiments. As conventional klystrons, modern gyroklystrons consist of modulating input cavity, several bunching cavities

Table 17 Step tuning of MIT gyrotron oscillators (with large MIG [993, 994]) 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 [993, 994]	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

and output cavity. Gyrotrons and gyroklystrons are devices which usually utilize only weakly relativistic electron beams ($V_o < 100$ kV, $\gamma < 1.2$) with high transverse momentum (pitch factor $\alpha = v_\perp/v_z > 1$) [381–384]. The wave vector of the radiation in the cavity is almost transverse to the direction of the external magnetic field ($k\perp >> k_z$, and the Doppler shift is small) resulting, according to eqs. (1) and (2), in radiation near the electron cyclotron frequency or one of its harmonics:

$$\omega \cong s\Omega_c \ , \qquad s = 1, 2, \ldots \tag{5}$$

In the case of cylindrical cavity tubes (see Figs. 1 and 2) the operating mode is close to cutoff ($v_{ph} = \omega/k_z >> c$) and the frequency mismatch ω - $s\Omega_c$ is small but positive in order to achieve correct phasing, i.e., keeping the electron bunches in the retarding phase [381–384]. The Doppler term $k_z v_z$ is of the order of the gain width and is small compared with the radiation frequency. The dispersion diagrams of fundamental and harmonic gyrotrons are illustrated in Figs. 3 and 4, respectively. The velocity of light line is determined by $\omega = ck_z$. For given values of γ and R_o, a mode represented by its eigenvalue X_{mn} and oscillating at angular frequency ω is only excited over a narrow range of B_o. Quasi-optical gyrotrons employ a Fabry-Perot mirror resonator perpendicular to the electron beam, also providing $k_\perp >> k_z$ (Fig. 2). By variation of

Table 18 Step tuning of MIT gyrotron oscillator (with small MIG [993, 994]) 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 [993, 994]	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

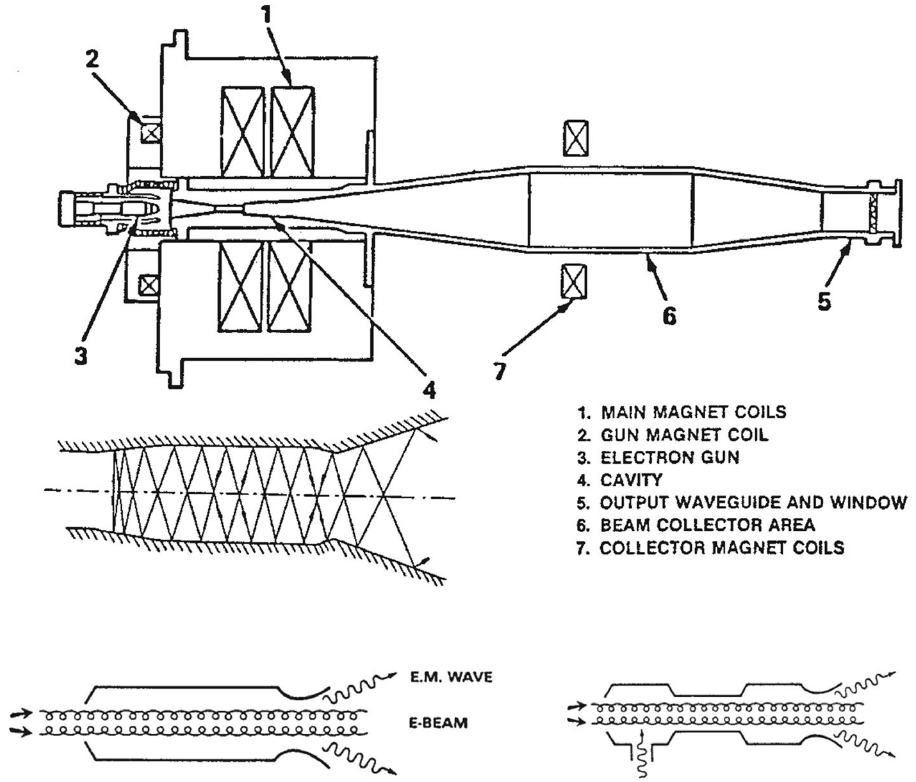


Fig. 1 Schematic of VARIAN (CPI) CW gyrotron oscillator and scheme of irregular waveguide cavities of gyromonotron oscillator (left) and two-cavity gyroklystron amplifier (right)

the magnetic field, a sequence of discrete modes can be excited. The frequency scaling is determined by the value of B_o/γ. Modern high-power high-order volume

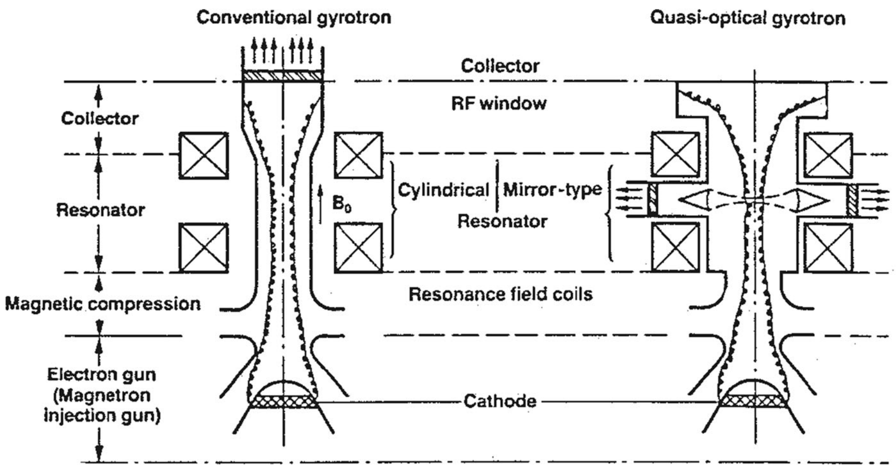


Fig. 2 Principle of a conventional gyrotron with cylindrical resonator and of a quasi-optical gyrotron with mirror resonator

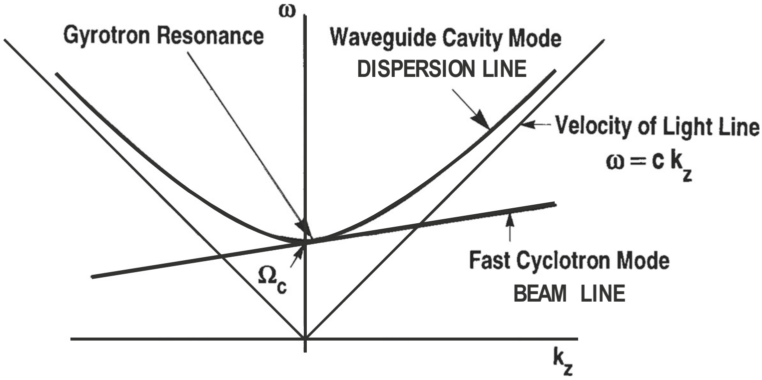


Fig. 3 Dispersion diagram of gyrotron oscillator (fundamental resonance)

mode CW gyrotron oscillators for fusion plasma applications employ an internal quasi-optical (q.o.) mode converter with lateral microwave output [381–397] and a single-stage depressed collector (SDC) for energy recovery (Tables 2, 3, 4, 5, 6, 7, 8, 9, 10) (Fig. 5). Highly efficient, advanced q.o. mode converters utilize waveguide launchers with optimized wall perturbation: helical-type [385–388, 396, 397], mirror-type [389–394], or hybrid-type [395]. Cavity expansion due to ohmic wall heating (skin effect) and partial electron beam space charge neutralization reduce the operating frequency by a few hundred MHz [398, 399]. Cyclotron harmonic operation reduces the required magnetic field for a given frequency by the factor s. However, the measured efficiencies high-frequency gyrotrons operating at higher harmonics ($s = 2$ and 3) are lower than those operating at the fundamental frequency [8–17, 339–347, 378–384].

At low voltages, the number of electron orbits required for efficient bunching and deceleration of electrons can be large, which means that the resonant interaction has a narrow bandwidth, and that the RF field may have moderate amplitudes. In contrast with this, at high voltages, electrons should execute only about one cyclotron orbit.

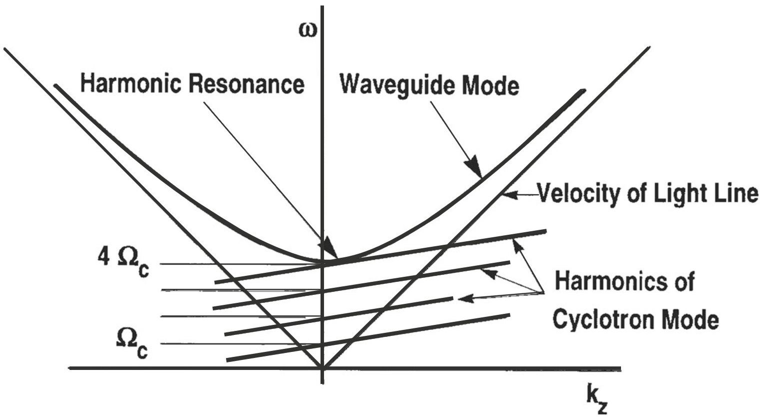


Fig. 4 Dispersion diagram of harmonic frequency gyrotron oscillator

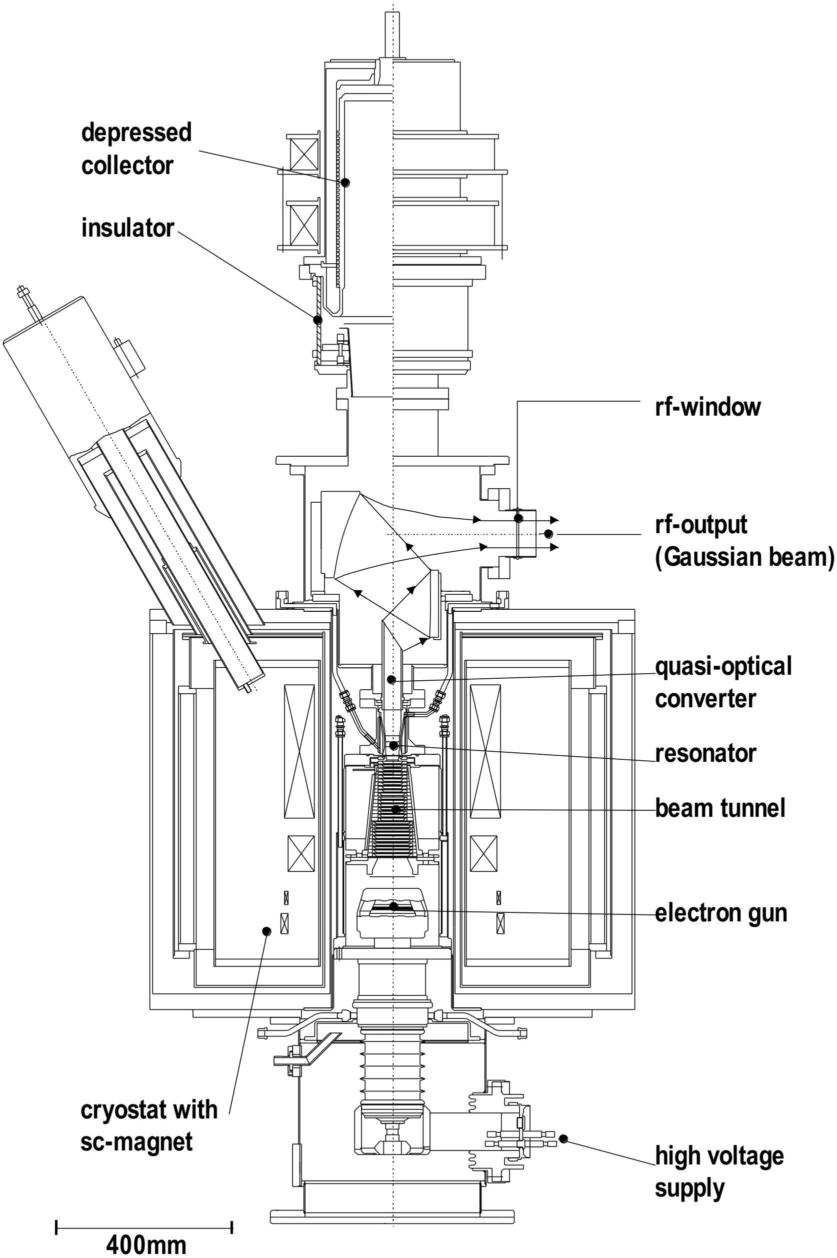


Fig. 5 Schematic layout of modern high-order volume mode gyrotron with quasi-optical mode converter and single-stage depressed collector

This requires correspondingly strong RF fields, possibly leading to RF breakdown, and greatly broadens the cyclotron resonance band, thus making possible an interaction with many parasitic modes.

3.2 Cyclotron Autoresonance Maser

In gyrotrons with highly relativistic beams (≥ 1 MeV), efficient interaction will lead to an average energy loss in the order of the initial electron energy. As a result, the change in the gyrofrequency is much larger than in the mildly relativistic case. It is therefore desirable to identify the condition under which such highly relativistic electron beams remain in synchronism with the RF field. A possibility for achieving synchronism is to utilize the interaction of electrons with EM waves propagating with a phase velocity close to the speed of light in the direction of the external magnetic field. In this case, the Doppler shift term $k_z v_z$ is large, and the appropriate resonance condition is

$$\omega \cong k_z v_z + s\Omega_c \tag{6}$$

If $v_{ph} \cong c$, the increase in cyclotron frequency due to extraction of beam energy (decrease of γ), nearly compensates the decrease in the Doppler-shift term. Therefore, if the resonance condition (6) is initially fulfilled, it will continue to be satisfied during the interaction. This phenomenon is called autoresonance, and the cyclotron maser devices operating in the relativistic Doppler-shifted regime are called cyclotron autoresonance masers (CARM) [18, 361]. Figure 6 shows how the Brillouin diagram of the fast cyclotron wave changes during the autoresonance interaction such that the working frequency ω remains constant even though both Ω_c and v_z are changing. The CARM interaction corresponds to the upper intersection and is based on the same instability mechanism as that of the gyrotron but operated far above cutoff.

The instability is convective, so feedback, e.g., by a Bragg resonator (see Fig. 7) [361] is required for a CARM oscillator and it is necessary to carefully discriminate against the other interactions corresponding to the lower frequency intersection in the dispersion diagram Fig. 6. The problem can be alleviated by employing the fundamental TE_{11} mode or the balanced HE_{11} hybrid mode (in circumferentially corrugated circular waveguide [101]) and properly choosing the system parameters to be within the stability limit. Compared to a gyrotron, there is a large Doppler frequency upshift of the output radiation ($\omega \cong \gamma^2 \Omega_c$) permitting a considerably reduced magnetic field B_o. Since

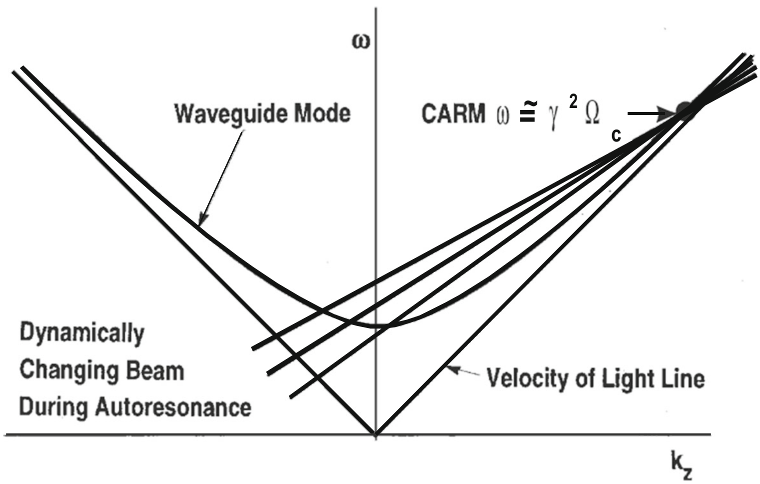


Fig. 6 Dispersion diagram of the cyclotron autoresonance maser (CARM)

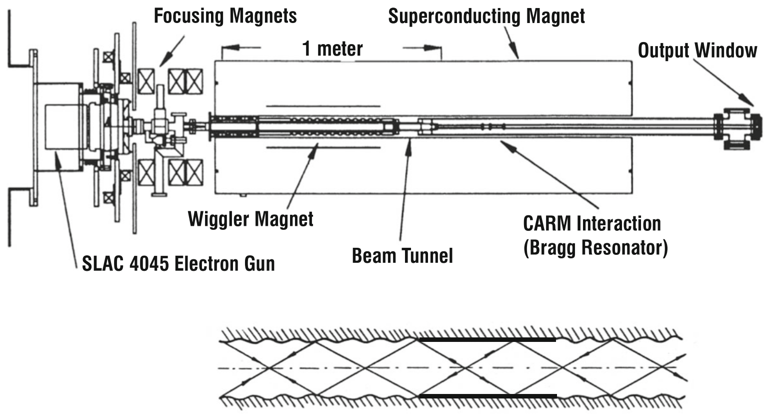


Fig. 7 Schematic of the long-pulse MIT CARM oscillator experiment and scheme of a Bragg resonator (Adapted from: [400] K.D. Pendergast et al., Int. J. Electronics, 72, No. 5 and 6, 983-1004 (1992))

the axial bunching mechanism can substantially offset the azimuthal bunching the total energy of the electron beam and not only the transverse component is available for RF conversion.

In contrast to the gyrotron, the CARM has an electron beam with low to moderate pitch factor ($\alpha <$ 0.7). The efficiency of CARMs is extremely sensitive to spread in the parallel beam velocity. The velocity spread $\Delta v_z/v_z$ must be lower than 1% to achieve the full theoretically expected efficiency of 40% [361, 400].

It has been suggested that an ECM operating in the Cherenkov regime ($v_{ph} < c$) may be an attractive alternative high-power microwave source. This slow-wave CARM utilizes the coupling between the slow cyclotron wave of the electron beam and the slow EM waves of the circuit at the anomalous Doppler cyclotron resonance eq. (6) with s = -1 or any other negative integer. Such a slow-wave ECM can be driven by an electron beam with predominant axial velocity as in conventional Cherenkov devices. Experimental demonstrations were reported in [401–404], in which dielectric loaded and corrugated waveguide slow-wave structures were used. Since the transverse wavenumber of slow waves is imaginary, their fields are localized near the structure wall, and, therefore, the electron beam should also propagate close to the wall to couple to these EM waves.

3.3 Gyro-TWT and Gyrotwystron Amplifier

From the theoretical point of view, the gyro-TWT differs from the CARM only in regimes of operation. The gyro-TWT utilizes a moderately relativistic electron beam to interact with a fast waveguide mode near the grazing intersection of the frequency versus wavenumber plot (see Fig. 8) where the resonance line is tangent to the EM mode. This produces high gain and efficiency because the phase velocities of the two modes are nearly matched and the group velocity of the waveguide mode is nearly equal to v_z. In the gyro-TWT regime ($\omega/k_z >> c$), the axial bunching mechanism is too weak to be of any significance. To benefit from autoresonance, the cutoff frequency should be reduced relative to the cyclotron frequency. The circuit employed in a gyro-TWT consists simply of an unloaded or loaded waveguide. Since no resonant structures are present, the gyro-TWT is potentially capable of a much larger bandwidth than a gyroklystron and thus can be used as a broadband amplifier in mm-wave radar and communication systems. Advanced devices employ tapered magnetic field and interaction circuit as well as two partially loaded stages in order to optimize the beam-wave interaction along the waveguide [405–408]. As in CARMs, it is necessary

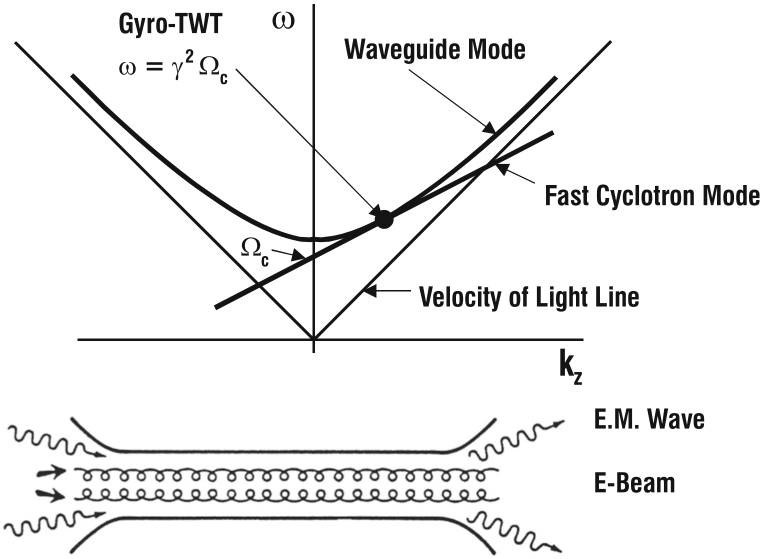


Fig. 8 Dispersion diagram and scheme of interaction circuit of Gyro-TWT amplifier

to carefully discriminate against the other interaction corresponding to the lower frequency intersection in the dispersion diagram Fig. 8 (see Section 3.4).

The sensitivity to velocity spread can be strongly reduced by coupling between the second harmonic cyclotron mode of a gyrating electron beam and the radiation field in the region of near-infinite-phase velocity over a broad bandwidth by using a cylindrical waveguide with a helical corrugation on its inner surface (helical, coupled-modes gyro-TWT) [409–411].

The gyrotwystron [9], a hybrid tube, is derived from the gyroklystron by extending the length of the drift section and replacing the output cavity with a sligthtly tapered waveguide section like in a gyro-TWT. The output waveguide section is excited by the beam of electrons that are bunched because of modulation in the input and bunching cavities. The gyrotwystron configuration has a broader bandwidth than the gyroklystron and can mitigate the problem of microwave breakdown at high-power levels, since the microwave energy density in the output waveguide can be much smaller than in a gyroklystron output cavity. The inverted gyrotwystron is a device consisting of the input waveguide, drift section, and output cavity [412]. The traveling signal wave in the input waveguide may induce a high harmonic content in the electron current density. Then the prebunched electron beam can excite phase-locked oscillations in the cavity at a harmonic of the signal frequency.

3.4 Gyro-BWO

If the electron beam and/or magnetic field are adjusted so that the straight fast-wave beam line crosses the negative k_z-branch of the waveguide mode hyperbola (see Fig. 9) then an absolute instability (internal feedback) with a "backward wave" occurs. In the gyro-BWO, the frequency of operation is now governed by the slope of the beam line, which is a function of v_z, and thus of the beam acceleration voltage V_o. Consequently, just as in the case of slow-wave BWOs (e.g., Carcinotron), the frequency of oscillations can be continuously changed very fast over a broad range, using V_o in place of B_o. However, here, in contrast to conventional BWOs, also the phase velocity is negative ($v_{ph} < 0$). There is a Doppler down shift in frequency ($\Omega_c/2 < \omega < \Omega_c$), so that very high magnetic fields are required for high-frequency operation.

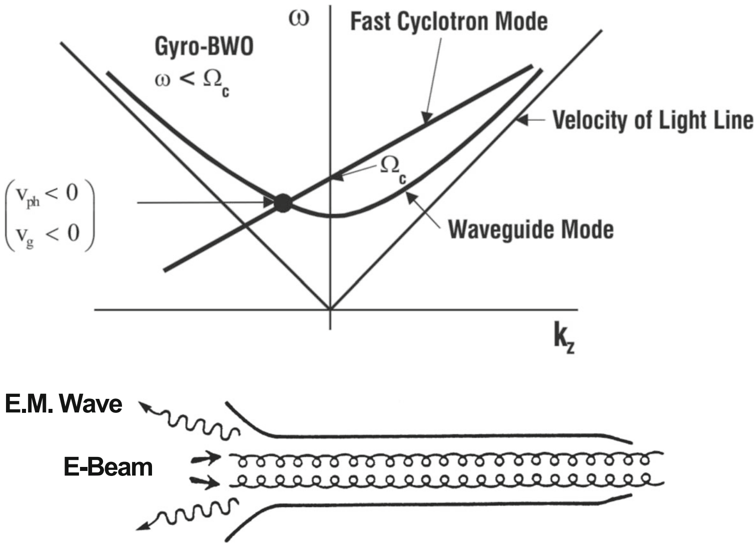


Fig. 9 Dispersion diagram and scheme of interaction circuit of Gyro-BWO

3.5 Overview on Gyro-Devices

Bunching of electrons in the gyrotron oscillator and in gyro-amplifiers has much in common with that in conventional linear electron beam devices, namely, monotron, klystron, TWT, twystron and BWO [9]. In both cases the primary energy modulation of electrons gives rise to bunching (azimuthal or longitudinal) which is inertial. The bunching continues even after the primary modulation field is switched off (in the drift sections of klystron-type and twystron-type devices). This analogy suggests the correspondence between conventional linear-beam (O-type) devices and various types of gyro-devices. Table 1 presents the schematic drawings of devices of both classes.

In Tables 15, 20, 21, 35, and 36, two other microwave source types similar to, but also fundamentally different in one way or another from, the ECMs will be briefly considered. The large orbit gyrotron (LOG) employs an axis-encircling electron beam in which the trajectory of each electron takes it around the axis of the cylindrical interaction region [378, 413]. For the operating modes TE_{mn} a strong selection rule is valid: $m = s$ in Eq. (5). Peniotron and gyro-peniotron are driven by an interaction that is phased quite differently from the ECM interaction; in practice, the peniotron and ECM mechanisms compete [379–382, 414].

4 Magnicons and Gyroharmonic Converters

The magnicon is a member of the class of scanning-beam amplifier tubes [16, 415, 416]. It is a magnetized device that uses a fast-wave output cavity. Therefore, it can also be grouped with gyro-devices in which electrons gyrating in an external magnetic field emit bremsstahlung radiation near the cyclotron resonance. In the earliest version of the magnicon, an electron beam was deflected in the unmagnetized input cavity, using a rotating TM_{110} mode and after an also unmagnetized drift space, the deflected beam is spun up to high transverse momentum by entry into a strong magnetic field at the entrance of the output cavity.

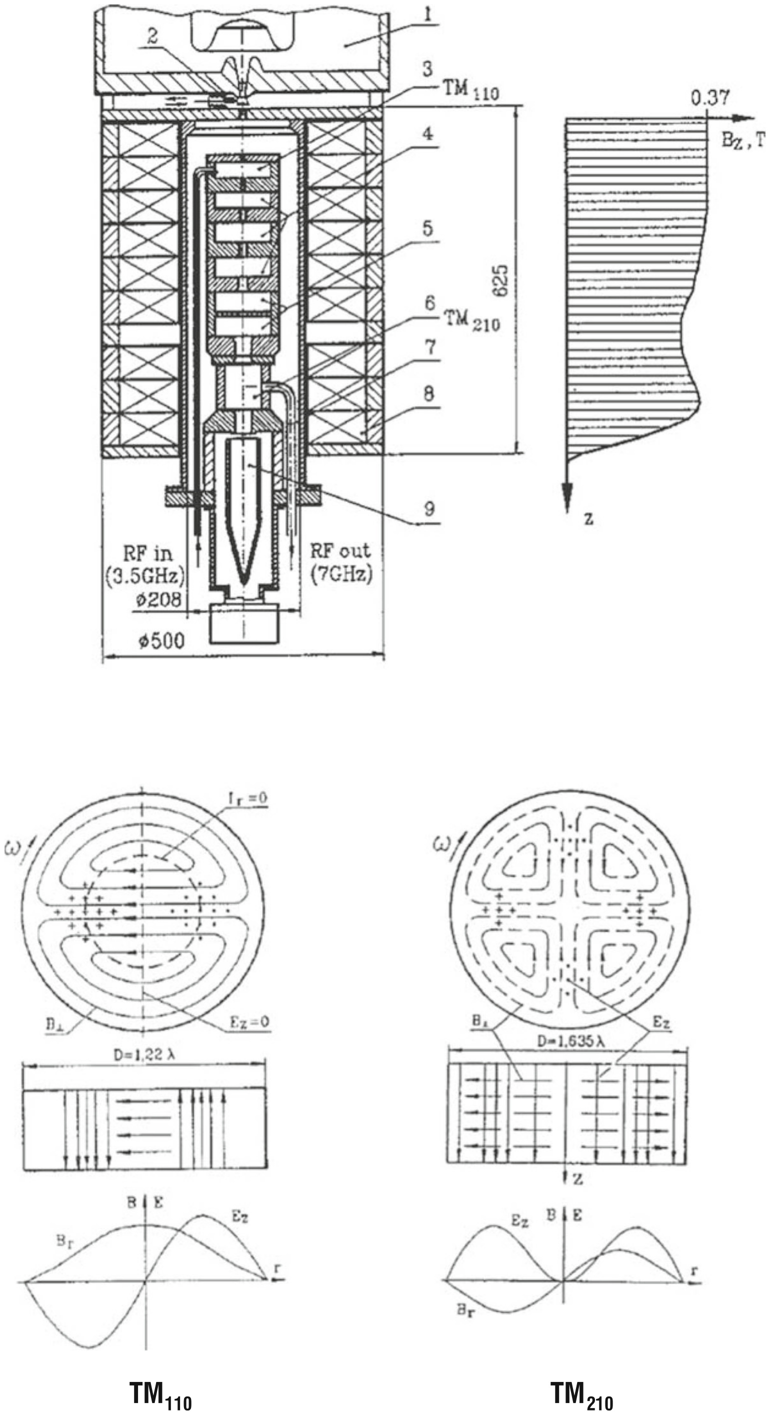


Fig. 10 Schematic layout of the magnicon: 1—electron source; 2—vacuum valve; 3—drive cavity; 4—gain cavity; 5—penultimate cavity; 6—output cavity; 7—waveguide (× 2); 8—solenoid; 9—collector (Adapted from: [415] O.A. Nezhevenko, IEEE Trans. on Plasma Science, 22, No. 5, 756-772 (1994))

As a result of the phase-synchronous transverse deflection of the electron beam as a whole, the beam electrons entering the output cavity execute Larmor motion whose entry point and guiding center rotate in space around the cavity axis at the drive frequency. In the output cavity, the beam is used to drive a cyclotron-resonant fast-wave interaction with a synchronously rotating TM_{110} mode that extracts principally the transverse beam momentum. This interaction can be highly efficient, because the magnicon beam is fully bunched in space and in the gyro-phase, so that the phase bunching produced by the cyclotron maser instability is not required. With all the electrons decelerated identically, very high efficiencies can be achieved.

Later, higher perveance versions of the magnicon have been developed [416, 417], in which a fully magnetized electron beam is spun up to a high transverse momentum in a sequence of deflection cavities containing synchronously rotating TM_{110} modes, the first driven by an external RF source (Fig. 10). In addition, the output cavity can operate in the mth harmonic of the drive frequency by using TM_{m10} modes with $m > 1$, permitting extension of magnicon operation to higher operating frequencies. Again, the point of injection of the beam into the output cavity as well as the entry gyro-phase, rotate synchronously with a rotating RF mode of the output cavity. This makes possible much higher efficiencies than in most other gyro-devices. The key to the efficiency of these new magnicon designs is to spin the beam up to high transverse momentum ($\alpha > 1$) without producing large spreads in energy and gyro-phase, so that the output cavity interaction will remain coherent over the entire ensemble of electrons, and not just synchronous in time. This requires great care in the design of the deflection cavities, in particular of the penultimate deflection cavity that produces more than half of the beam spin up. Since these spreads are generated by the fringing fields of the beam tunnel apertures in the deflection cavities and the output cavity, it also requires the use of a very small initial electron beam radius.

A summary of the development status of magnicons is given in Table 35.

A similar “scanning-beam” microwave device is the gyroharmonic converter in which dubbed “co-generation” arises from a near match in group and phase velocities between the input cavity TE_{11} mode at frequency ω and the TE_{72} mode at frequency 7ω in a cylindrical waveguide [418]. This match allows efficient power transfer into the 7th harmonic from a fundamental frequency wave that energizes an electron beam via cyclotron autoresonance acceleration (CARA). Theory indicates that high conversion efficiency can be obtained for a high-quality beam injected into CARA, and when mode competition can be controlled.

Generation of 0.5-MW power (3-μs pulse duration, 5 % efficiency) at 8.57 GHz (3rd harmonic of 2.856 GHz) in the TE_{31} mode has been observed in experiments using a 350-kV, 30-A electron beam [418–420].

5 Free Electron Masers

Free electron lasers (FELs) differ from the other high-power microwave sources considered in this report in that they have demonstrated output over a range of frequencies extending far beyond the microwave spectrum, well into the visible and ultraviolet range [361–368, 379, 380]. To achieve this spectral versatility, FELs exploit relativistic beam technology to upshift the electron “wiggle” frequency by an amount roughly proportional to γ^2 (see Fig. 11 and Section 2). In this respect, perhaps a more descriptive name is that coined by R.M. Phillips [421]: UBITRON, for an “undulated beam interaction electron” tube. The magnetostatic wiggler is the most common, but not the sole means, for providing electron undulation. An electrostatic wiggler or the oscillatory field of a strong electromagnetic wave can also play this role. Devices with such electromagnetic wigglers

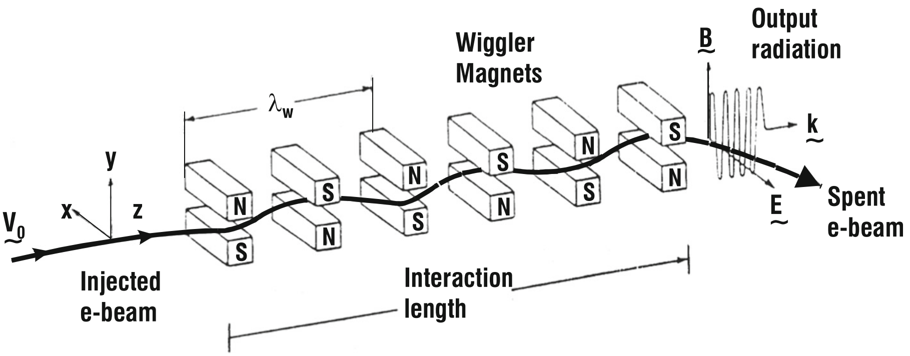


Fig. 11 The basic FEM configuration. Electrons in an injected electron beam undulate in the periodic magnetic field of the wiggler (Adapted from: P. Sprangle et al., Nucl. Instrum. Meth. Phys. Res., A239, No. 1, 1 (1985))

are sometimes called scattrons [9, 18, 361]. The distinction between long-wavelength free electron maser (FEM) ($\lambda \geq 0.5$ mm) and short-wavelength FELs is natural because higher current and lower energy beams are typically employed in this regime and space-charge effects are more important. In particular, the dominant interaction mechanism is often coherent Raman scattering. Also, while short-wavelength FELs excite optical modes, dispersion due to the beam dielectric effects and finite transverse dimensions in the drift tubes and cavities are important effects at longer wavelengths. A low power (3-W, 2-ms pulses) FEL operating at radio frequencies (FER) employing a 420 V, 0.2 A electron beam holds the world record for long wavelength ($f = 266$ MHz, $\lambda = 1.1$ m, $\lambda_w = 0.04$ m, $B_w = 0.04$ T) [422].

The FEM appears to be potentially capable of fulfilling all the requirements for a frequency tunable high-power mm-wave source. Coverage of the entire frequency range of 130–260 GHz presents no severe problems, and even higher frequencies are quite feasible [4, 423–434]. Rapid tunability over more than ± 5% could be obtained by variation of the electron beam energy. The interaction occurs in an interaction circuit operating in low-order modes, which have very good coupling to a Gaussian beam output. The relatively low RF wall loading and the use of high electron beam energy (> 0.5 MeV) and a multi-stage depressed collector are compatible with a high unit power at efficiencies around 50% if the electron beam interception could be maintained at an acceptable level. A survey of FEM development status (experiments) is presented in Table 38. It is a great pity that the FOM-FEM project [423–433] was terminated in the autumn of 2001.

The highest CW power generated by a FEM is 36 W (X-band) [435] whereas the pulsed IR-FEL at the Thomas Jefferson National Accelerator Facility obtained a record average power of over 10 kW in the band from 1 to 14 μm (14.2 kW at 1.6 μm) and has the capability of more than 1 kW in the 250- to 1000-nm range. A recirculated electron beam power of up to 1 MW (Energy Recovering Linac) has been demonstrated resulting in an overall efficiency of approximately 2% [367, 368, 436–441]. The average output power in the THz regime is 100 W (train of sub-picosecond pulses).

The first stage of the Novosibirsk High Power Free Electron Laser (NovoFEL) had been commissioned in 2003. This 12-MeV THz-FEL generates coherent radiation, tunable in the range of 90–240 μm (3.33–1.25 THz), 60–117 μm, and 40–80 μm at the first, second, and third harmonics, respectively, with the corresponding maximum average output powers of 0.5 kW, 100 W, and 30 W. The maximum peak power is 0.5 MW (bunch duration: approx. 100 ps), the relative line width is 0.2–2% [442, 443].

The two-orbit energy recovery linac stage was assembled and commissioned in 2008. The first lasing of the two-stage THz-FEL (22 MeV) was achieved in 2009, providing radiation in the wavelength range 40–90 μm (bunch duration: 10–20 ps) at an average output power between 0.5 and 1 kW (2 MW peak power) with a maximum gain of 40%. The relative linewidth is 0.2–1%.

First lasing of the three-stage THz-FEL (42 MeV, 4 orbits), which is expected to deliver 1 kW average power at a pulse repetition rate of 3.75 MHz in the wavelength range of 5–10 μm, was obtained in 2015. The radiation wavelength was 9 μm at an average power of approximately 100 W [444–447].

The 200-ns LIU-3000 Induction LINAC (0.8 MeV, 200 A, 200 ns) FEM at JINR Dubna [448–450] has been operated as FEM multiplier ($n = 1$ (TE_{11}) 24 GHz, 5 MW; $n = 2$ (TE_{21}): 48 GHz, 1.5 MW; $n = 3$: 72 GHz, 0.1 MW) and as 2nd harmonic FEM oscillator.

A table, summarizing the parameters and the state-of-the-art of IR/THz FELs from around the world, is being continuously updated by J. M. Knopf (Helmholtz-Center Dresden-Rossendorf (HZDR), Germany): https://www.hzdr.de/db/Cms?pOid=56940.

6 Gyrotron Oscillators and Microwave Vacuum Windows for Plasma Heating

Tables 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, and 13 present the current status of gyrotrons and RF vacuum windows for ECRH&CD in fusion plasmas.

Design studies on 4 MW, 170 GHz and 2 MW, 240 GHz coaxial-cavity gyrotrons for future fusion reactors were performed at KIT [877–880]. 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.

The KIT 1 MW $TE_{22,6}$ 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 [116]. 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%). These efficiencies where obtained without collector depression [883].

A specific feature of the coaxial gyrotron design is that it allows electron beam energy recovery and very fast frequency tuning by biasing the coaxial insert [869–872]. 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, step frequency tuning between the 165.1-GHz nominal mode and its azimuthal neighbors at 162.8 GHz and 167.2 GHz (see Table 10) was obtained. In addition, operating in the nominal $TE_{31,17}$ mode, continuous frequency pulling within 70 MHz bandwidth was achieved [825].

In order to define the appropriate concepts for the development of 1 MW, CW mm-wave windows one has to compare the thermophysical, mechanical and dielectrical parameters of possible window materials related to the load-failure resistance R' and the power-transmission capacity P_T at different temperatures [84–89, 102, 919]. The features of beryllia, boron nitride, silicon nitride (Kyocera SN-287), sapphire, Au-doped silicon, CVD diamond and silicon carbide at room temperature and of sapphire, Au-doped silicon and CVD diamond at cryo-temperatures are summarized in Tables 11 and 12, where

$$R' = k \cdot \sigma_B \cdot (1 - \nu)/E \cdot \alpha \tag{7}$$

$$P_T = R' \rho \cdot c_p((1 + \varepsilon'_r) \tan\delta). \tag{8}$$

For a 1 MW, CW mm-wave window the parameters R' and P_T should exceed 250 and 100, respectively.

Comparison of R' and P_T for the 4 materials BeO, BN, Si_3N_4 and sapphire shows that there is no chance to use these dielectrics for edge-cooled, single-disk CW windows at room temperatures. Experiments at CPI in the US and at NIFS and JAEA (now QST) in Japan confirmed that even a double disk FC75-face-cooled sapphire window has a CW-power limit of 0.3–0.4 MW. Nevertheless, these materials are widely used at lower frequencies and pulse operation.

At LN_2-temperature 77 K (LNe-temperature 30 K) sapphire has a thermal conductivity of 900 (20000) W/mK and a loss tangent of $5.7 \cdot 10^{-6}$ ($2 \cdot 10^{-6}$) leading to R' = 130 (2870) and $P_T = 71$ (4460). The LN_2-edge-cooled sapphire window of the 118 GHz TED gyrotron (0.5 MW, 210 s) [632–642] operates close to the allowable lower limits of R' and P_T. However, the mechanical features and the required cooling auxillaries make such cryo-windows very complicated. Au-doped silicon at temperatures somewhat lower than 0 °C could avoid a thermal runaway and transmit 1 MW, CW; however, this material is too brittle and tends to mechanical cracking [907].

Using the available material parameters and employing various beam profiles, finite element computations revealed several options for 170 GHz, 1 MW, CW operation given in Table 13 [84–89, 102, 919]. The CVD diamond options 2 and 3 being water cooled are preferred for their simplicity, in particular for use as torus window.

A wide-band CVD-diamond Brewster window in corrugated HE_{11} waveguide with 32-mm inner diameter has been tested at 110 GHz using 0.5 s pulses with powers up to 350 kW [951–953].

7 Harmonic and Very High-Frequency Gyrotron Oscillators

Operating at the fundamental, the 2nd harmonic or the 3rd harmonic of the electron cyclotron frequency 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, 1 ms) (Tables 14, 15, 16, 17, and 18) [182–305, 920–1016].

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 operated at the 3rd harmonic 285 GHz in the TE_{03} mode [1017–1021]. Simultaneous generation at the 2nd (37.5 GHz) and 4th (75 GHz) harmonic (140 W at 60 kV and 6 A) was obtained by a self-excited gyromultiplier with single, sectioned cavity [1022, 1023]. A high-harmonic sectioned TE_{35} mode gyrotron of IAP Nizhny Novgorod produced 0.5 kW at 740 GHz with 0.9% efficiency [1024–1026].

8 Gyrotrons for Technological Applications

The state-of-the-art of gyrotrons for technological applications is summarized in Table 19. IAP Nizhny Novgorod and GYCOM have developed a dual-frequency materials processing system

Table 19 Performance of present CW gyrotron oscillators for technological applications

Institution	Frequency [GHz]	Mode		Power [kW]	Efficiency [%]	Voltage [kV]	Magnet
		Cavity	Output				
CPI[1)], Palo Alto [14, 19, 954]	28	TE_{02}	TE_{02}	15	38	40	room temp.
	28 ($2\Omega_c$)	TE_{02}	TE_{02}	10.8	33.6	30	room temp.
	60	TE_{02}	TE_{02}	30	38	40	cryo. mag.
CPI, NIFS [79–81, 474–477] Palo Alto, Toki	84	$TE_{15,3}$	TEM_{00}	50	14	80	cryo. mag.
GYCOM/IAP Nizhny Novgorod, [1, 15, 109, 129, 162–164, 317–321, 324, 329–336, 339–344, 481, 718, 719, 955, 1027–1042]	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 freq. switching
	28.25 ($2\Omega_c$)	TE_{12}	TE_{12}	12	20	25	PM, 68 kg[2)]
	31.8-34.8	TE_{11}	TE_{11}	1.2	40	12	mech. tun.
	35.5-37.5	TE_{01}	TE_{01}	0.5	15.3	16	mech. tun.
	35.15	TE_{02}	TE_{02}	9.7	43	25	cryo. mag.
	35	TE_{02}	TEM_{00}	10-50	30-40	25-30	cryo. mag.
	37.5	TE_{62}	TEM_{00}	20	35	30	cryo. mag.
	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 [1043]	28 ($2\Omega_c$)	TE_{12}	TE_{12}	22.5	43	23.4	room temp.

Table 19 (continued)

Institution	Frequency [GHz]	Mode		Power [kW]	Efficiency [%]	Voltage [kV]	Magnet
		Cavity	Output				
MICRAMICS, San Jose [1044]	24.1 ($2\Omega_c$)	TE_{22}	TEM_{mixed}	5	25	23	room temp.
			TE_{22}	10	25	23	room temp.
MITSUBISHI, Amagasaki [338, 1045–1047]	28 ($2\Omega_c$)	TE_{02}	TE_{02}	10	38.7	21	PM, 600 kg[2)] tapered B
UESTC, Chengdu [1048]	37.5	TE_{13}	TE_{13}	57 (0.4 average)	9	50.5	room temp.
UNIV. Fukui, IAP Nizhny Novgorod/GYCOM [323, 1049–1056]	300	$TE_{22,8}$	TEM_{00}	2.3	16.4	14	cryo. mag.

[1)] Communications & Power Industries, formerly VARIAN, [2)] *PM* permanent magnet employing a 15-kW, 28-GHz gyrotron and a 2.5-kW, 24.1-GHz tuneable gyro-BWO (see Tables 33 and 34) [324, 332, 333]. This system has been installed at the University of Fukui, Japan.

9 Relativistic Gyrotrons

Table 20 Present development status of relativistic gyrotron oscillators

Institution	Frequency [GHz]	Mode	Voltage [MV]	Current [kA]	Power [MW]	Efficiency [%]	Type
IAP, Nizhny Novgorod [1057–1067]	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	
	55.7 ($2\Omega_c$)	$TE_{11,2}$	0.22	0.0325	2	28	
	79–107	TM_{1n}	0.5	2–6.5	30	3–1	slotted echelette cavity, $n = 3–10$
	94.4	$TE_{12,5}$	0.24	0.103	5.6	23	TEM_{00} output and counter rotating input for injection locking
IAP, Nizhny Novgorod	10	TE_{13}	0.3	0.4	25	20	slotted cavity
	10	TE_{13}	0.3	1.0	60	15	plasma-filled slotted cavity
Lebedev/ General Phys. Inst. Moscow [1058, 1068–1070]	40	TE_{13}	0.4	1.3	25	5	slotted cavity
KIPT, Kharkov [1071]	12	TE_{13}	0.12	8.0	60	6.3	plasma filled slotted cavity
UNIV. Michigan [1072–1078]	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. [1079–1082]	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) *)	
			1.15	2.5	275	10	
	35	TE_{13}	0.9	0.65	35	6	slotted cavity
Tomsk Polytech. Inst. [1083]	3.1		0.75	8.0 (30)	1800	8	also vircator interaction
UNIV. Niigata [1084]	18.2	TE_{01}	0.08	0.5	0.2	0.55	
UNIV. Strathclyde [1085–1090]	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 21 Relativistic large orbit harmonic pulse gyrotrons with axis-encircling electron beam. The 21.6- to 74.9-GHz experiments at IAP used an explosive-emission cathode with kicker ($\tau = 10$ ns) and the 115- to 469-GHz experiments employed a quasi-Pierce type thermionic 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 [413, 1020, 1091–1099]	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 [1100]	98–144	TE_{n1}	n	0.325	0.045(7)	1.3	9(0.06)

10 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 [382, 451]	92	TEM_{00q}	90	10	10	
SPC[1)], Lausanne [105, 106, 382, 1101]	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 [1102]	100	TE_{061}	260	6.5	0.04	Echelette Cavity
MIT, Cambridge [1103, 1104]	136	$HE_{061}^{()}$	83	18	0.003	Confocal
	114.3	$HE_{051}^{()}$	75	16	0.003	Slot-Cavity
Moscow-State UNIV. [1105]	35	TEM_{00q}	1	15	CW	
	95	TEM_{00q}	1	15	CW	
NRL, Washington D.C. [881, 1106, 1107]	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 [602]	112	TEM_{00q}	100	12	5	
	120	TEM_{00}	26	10 (DEB)	3	
UESTC, Chengdu [1108–1110]	395.35 ($2\Omega_c$)	$HE_{011,1}^{()}$	6.44	3.4	0.1	Confocal slot-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

11 Cyclotron Autoresonance Masers

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	$TE_{11}{}^{*}/TE_{21}$ ($2\Omega_c$)	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	$TE_{11}{}^{*}/TE_{21}$ ($2\Omega_c$)	13	26 (0.65)	–	1.24	0.5	0.1 (4)	CARM-gyrotron
	40	TE_{11}	6	22 (0.44)	–		0.46	0.06 (0.3)	oscillator
IAP, IHCE, JINR	50	TE_{11}	30	10	–	0.7	1.0	0.3	oscillator
IAP	66.7	TE_{21}	15	3	–	0.6	0.5	1.0	oscillator
IAP, IHCE, JINR	68	TE_{11}	50	8	–	1.0	1.2	0.5	oscillator
IAP	69.8	TE_{11}	6	4	–	0.6	0.35	0.4	oscillator
IAP [1091, 1092, 1111–1120]	125	TE_{41}	10	2	–	0.9	0.5	1.0	oscillator
LLNL Livermore [1121]	220	TE_{11}	50	2.5	–	3.0	2.0	1.0	oscillator
MIT Cambridge	27.8	TE_{11}	1.9	5.3	–	0.6	0.45	0.080	oscillator
[400, 1122, 1123]	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 [1124]	35,70–90	TE_{61}	0.02	0.002	–	1.0	0.6	0.2 (100)	oscillator
UNIV. Michigan [1125, 1126]	15	TE_{11}	7	1.5	–	0.45	0.4	1.2	oscillator
UNIV. Strathclyde [1127–1129]	13	TE_{11}			–	0.3	0.4	0.04	oscillator
	14.3 ($2\Omega_c$)	TE_{21}	0.18	4 (0.4)	–	0.2	0.3	0.015 (0.15)	oscillator

* Output

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 [401]	9.5	TM_{01}	35	3.5	–	1.15	0.4	2.5	oscillator corr.waveguide
Tomsk Polytechn. Inst. [402]	25		20	0.2	–	0.64	0.9	14	oscillator diel.waveguide
UNIV. Niigata, NIFS, UNIV. Maryland [403]	19.5	TM_{01}	0.2	3.8	–	0.9	0.035	0.15	oscillator corr.waveguide
UNIV. Yale, NRL, Washington D.C. [404]	6.2	TE_{01}	0.02	10	53	0.2	0.05	0.005	amplifier diel.waveguide

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

12.1 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[1)], Palo Alto [19, 379]	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. [354, 555, 1130–1137]	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 [1138, 1139]	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 [1140–1154]	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	TE_{02}	2	300(230)	22(30)		0.3	2-cav. Gyrotron
	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 [1155–1157]	35 ($2\Omega_c$)	TE_{02}	3	212	16	24	0.44	
Kwangwoon Univ., Seoul [1158]	27.85	TE_{01}	5	150	26	50	0.1	
NRL, Washington D.C. [351–353, 379, 881, 1159–1170]	4.5	TE_{10}	3	54	30	30	0.4	
	34.95	TE_{01}	2	210	37	24	0.35	

Table 25 (continued)

Institution	Frequency [GHz]	Mode	No. of cavities	Power [kW]	Efficiency [%]	Gain [dB]	BW [%]	Type
	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. pow.xBW
UESTC, Chengdu [1171]	34.9 ($2\Omega_c$)	TE_{01}–TE_{02}	4	250 (5 av.)	24	36	0.4	

12.2 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, Litton, NRL, U.M. [351–354, 461, 1130–1137]	93.8	TE_{01}	4	10.1	33.5	32	0.45	(92 kW, 11% duty)
	94.2	TE_{01}	5	10.2	31	33	0.75	(102 kW,10% duty)
IAP N. Novgorod [1142]	9.17	TE_{11}	2	0.7	70	22	0.3	
IAP/ISTOK Moscow [1143, 1146]	91.6	TE_{01}	4	2.5	25	31	0.36	

QOGK quasi-optical gyroklystron, *SDC* single-stage depressed collector

[1)] Communications & Power Industries, formerly VARIAN

12.3 Relativistic Pulse Gyroklystron

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 [1172–1182]	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 [345–348, 1183–1196]	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	

12.4 Weakly Relativistic Gyro-TWTs

Table 28 Present development status of weakly relativistic gyro-TWTs (short pulse)

Institution	Frequency [GHz]	Mode	Power [kW]	Efficiency [%]	Gain [dB]	Bandwidth [%]	Type
BVERI, Beijing [1197–1203]	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
CPI[1)], Palo Alto [19, 354–356, 379, 555, 1137, 1204–1207]	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 [1208]	10(2Ω_C)	TE_{-21}/TE_{+11}	180				gridded gun
IAP, Nizhny Novgorod [1209–1223]	36.3(2Ω_C)	TE_{-21}/TE_{+11}	180	27	25	10	cusp gun with axis-encircl. beam 3 µs
	34.3(2Ω_C)	TE_{-21}/TE_{+11}	120	23	20	6	long pulse 110 µs
			160 (7.7)	36(33)	27	1.3 (7.5)	250-µs pulse (CW)
IECAS, Beijing [1228–1130]	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 [1227–1244]	140	$HE^{()}_{061}$(q.o.)	30	12.5	29	1.6	at 0.875 kW 400 ps
			0.55	0.4	35	0.9	modulation
	250	TE_{03}-like	0.045	0.4	38	3.2	pulse PBG, 260 ps pulses
NRL, Washington D.C. [379, 1245–1251]	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-encircl. 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 [1252–1264]	9.3	TE_{10}	55	11	27	11	diel. coat. waveg.
	10.4 (3Ω_C)	TE_{31}	6	5	11	3	axis-encirl. beam
	15.7 (2Ω_C)	TE_{21}	207	12.9	16	2.1	slotted waveg.
	16.2 (8Ω_C)	TE_{81}	0.5	1.3	10	4.3	axis-encircl. beam
	92	TE_{01}	140	22	60	2.2	heavily loaded + short copper stage
NTHU, Hsinchu [127–1271]	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 [1272–1284]	16	TE_{11}	200 (20 av.)	23.8	43	16.3	3-stage lossy (long)
	16	TE_{01}	420	23	35	10	periodic lossy circuit
	34	TE_{01}	165 (11.5 av.)	27.5	45	10	lossy circuit
	48	TE_{01}	158	22.6	47	7	periodic lossy circuit
	92.5	TE_{01}	110	19.3	69.2	4.2	lossy circuit
UNIV. Kwangwoon [1285]	14.4	T E_{10}	14.9	18	27	7	two-stage circuit
UNIV. Strathclyde [1286–1292]	93(2Ω_C)	TE_{-21}/TE_{+11}	3.4	4.2	37	5.8	cusp gun with axis-encircl. beam
UNIV. Tel Aviv [1293]	7.3	TE_{10}	0.8	12	26		3-stage output

1) Communications & Power Industries, formerly VARIAN

12.5 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 UNIV. Strathclyde [409–411, 1209–1211, 1294–1298]	9.4 ($2\Omega_C$)	TE_{-21}/TE_{+11}	1.1	29	37	21	helical waveguide with $\Delta m = 3$ perturb. Axis encircl. E-beam
	36.5 ($2\Omega_C$)	TE_{-21}/TE_{+11}	3.0	27	33	20(ΔB)	see above
MIT, Cambridge [1299]	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. *) [1300, 1301]	35	TE_{11}	20	11	30		explosive-emission gun, bifilar helical wiggler
UNIV. Strathclyde [1302–1307]	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

12.6 Weakly Relativistic Pulse Gyrotwystrons

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

Institution	Frequency [GHz]	Mode		Power [kW]	Efficiency [%]	Gain [dB]	BW [%]
		Cavity	TW section				
CPI[1)], Palo Alto [352, 354, 461, 1137]	94	TE_{01} (4 cav.)	TE_{01}	59 (5.9 av.)	14.9	35	1.6
NRL, Washington D.C. [1308]	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. [1309, 1310]	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

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

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

Institution	Frequency [GHz]	Mode: Cavity	Mode: TW section	Power [kW]	Efficiency [%]	Gain [dB]	BW [%]
IECAS [1311–1318]	33.1	TE_{01}/coupled cavity ($2\Omega_c$) TE_{02}/TE_{03}	$TE_{03}(\Omega_c)$	75	7.1	25	1.1
Seoul National UNIV. [1319]	33.9	TE_{10}	$TE_{10}(3\Omega_c)$	10^{-4}	2×10^{-3}	LO-gyro-TWT	3.8
UNIV. Maryland. [412, 1320–1325]	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}							

12.8 Relativistic Pulse Gyrotwystrons

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

Institution	Frequency [GHz]	Mode: Cavity	Mode: TW section	Power [MW]	Efficiency [%]	Gain [dB]	BW [%]
UNIV. Maryland [1196, 1326]	9.878	TE_{01}	TE_{01}	21.6	21	25.5	
	19.76	TE_{01} (9.88GHz)	$TE_{02}(2\Omega_c)$	12	11	21	

12.9 Weakly Relativistic Pulse Gyro-BWOs

Table 33 Experimental results on weakly relativistic pulse gyro-BWOs (short pulse)

Institution	Frequency [GHz]	Mode	Power [kW]	Efficiency [%]	Bandwidth [%]	Type
UNIV. Strathclyde IAP N. Novgorod [1327–1330]	8.6 (2Ω_C)	TE_{+21}/TE_{-11}	65	16.5	17	quasi-Pierce gun with kicker
IAP, N. Novgorod KIT[1)], Karlsruhe [324, 1036, 1211–1218, 1331, 1332]	24.7 (2Ω_C)	TE_{+21}/TE_{-11}	7	15 23 (SDC)	5	MIG CW operation
IAP, Nizhny Novgorod [1215]	35-38 (2Ω_C)	TE_{+21}/TE_{-11}	34	7	15	quasi-Pierce gun with kicker
	35 (2Ω_C)	TE_{+21}/TE_{-11}	10	5	10	cusp gun with thermal cathode
IECAS, BVERI, Beijing [1333, 1334]	17.2	TE_{01}	48	10.5 21(SDC)	5	TE_{10}^r output
MIT, Cambridge, LLNL, Livermore [1335]	140	TE_{12}^c	2	2	9	
NRL, Washington D.C. [1336]	27.8	TE_{10}^r	2	9	3	electric tuning
	29.2	TE_{10}^r	6	15	13	magnetic tuning
NTHU, Hsinchu [1337–1345]	33.5	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
					1	
			164	41		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 [1346–1351]	95 (2Ω_C)	TE_{+21}/TE_{-11}	12	20	15.3	magnetic tuning, casp gun
UNIV. Utah [1352]	10	TE_{10}^r	0.72	10	8	

r rectangular waveguide, *c* circular waveguide

1) Formerly KfK, then FZK

12.10 Relativistic Pulse Gyro-BWOs (pulse duration = 0.02–1 μs)

Table 34 Experimental results on relativistic gyro-BWOs (short pulse)

Institution	Frequency [GHz]	Mode	Power [MW]	Efficiency [%]	BW [%]	Voltage [MV]	Current [kA]	Type
IAP, N. Novgorod [1353, 1354]	10 35(2Ωc)	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 Δm = 3 perturbation
UNIV. Kanazawa [1355, 1356]	9–13	TE_{10}^r	1	0.75 (0.02)	1	0.45	0.3(10)	
UNIV. Michigan [1357, 1358]	4–6 5–6 (2Ωc)	TE_{11} TE_{11}	55(30) 1	8(4.3) 0.15	1 4	0.7	1	
USAF Phillips Lab. Aberdeen [1359, 1360]	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

12.11 Peniotrons

Table 35 Experimental results of peniotrons

Institution	Frequency [GHz]	Mode	Output mode	Power [kW]	Efficiency [%]	Pulse length [ms]	Type
UC Davis [1361]	34.1 ($2\Omega_c$)	$TE_{11}{}^c$	4x $TE_{10}{}^r$	88	36	0.02	cusp gun
UNIV. Tohoku, Sendai [1362–1370]	10.0	$TE_{11}{}^r$	$TE_{11}{}^r$	10	36	0.02	magnetron-type cavity
	10.5 ($2\Omega_c$)	$TE_{31}{}^c$	$TE_{31}{}^c$	0.7	10		
				1.3	7		
	30.3 ($3\Omega_c$)	$TE_{41}{}^c$	$TE_{01}{}^c$	6.9	35 (75 electr.)		
				6.9	44(SDC) (92 electr.)		
	100 ($10\Omega_c$)	$TE_{11,1}{}^c$	$TE_{01}{}^c$	0.32	1.7 (5 electr.)		auto-res.
	10	$TE_{21}{}^c$	$TE_{21}{}^c$	1.5	25		

r rectangular waveguide, *c* circular waveguide, *SDC* single-stage depressed collector

12.12 Gyropeniotrons

Table 36 Experimental results of gyropeniotrons

Institution	Frequency [GHz]	Mode	Power [kW]	Efficiency [%]	Pulse length [ms]
UNIV. Tohoku, Sendai CANON[1)],	69.85 ($3\Omega_c$)	TE_{02}	8	6.75	0.2
Otawara UNIV. Fukui [1371]	140 ($3\Omega_c$)	TE_{03}	8	1	1

[1)] Formerly TOSHIBA

12.13 Magnicons

Table 37 Experimental results of magnicons

Institution	Frequency [GHz]	No. of Cavities	Voltage [MW]	Current [A]	Power [MW]	Efficiency [%]	Gain [dB]	Pulse length [μs]
BINP, Novosibirsk [415–417, 1372–1374]	0.915	3	0.3	12	2.6	73	30	30
	7.01 ($2\Omega_c$)	5	0.427	230	55	56	72	1.1
NRL, Washington D.C. [1375–1380]	11.424 ($2\Omega_c$)	7	0.48	210	25	25	59	0.2
					12	12	59	1.2
NRL, Yale UNIV./Omega-P [1380–1384]	34.3 ($3\Omega_c$)	7	0.455	187	17	19.5	47	0.1
					26	27	57	0.0005

BINP Budker Institute of Nuclear Physics

13 Free Electron Masers

The design parameters of the FOM-FEM [423–433, 1385] are presented below. The project was terminated in The Netherlands in the autumn of 2001 and shipped to Israel.

13.1 Electron Beam Line (with Multi-stage Depressed Collector)

Electron beam current :	12 A
Body current :	< 20 mA
Gun voltage :	80 kV
Type of gun	triode gun, cathode operated in space-charge limited regime
Normalized beam emittance	6 p mm mrad (before interaction)
Electron beam energy	1.35–2.0 MeV (130–250-GHz operation)
Acceleration/deceleration	electrostatic
Focusing system	solenoids in period focusing arrays
Pulse length	2–100 ms

13.2 Undulator

Period		40 mm
Pole gap		25 mm
Number of periods		34
Peak field strength	Section 1	0.20 T, 20 cells
	Section 2	0.16 T, 14 cells
Drift gap		35–60-mm length, adjustable
Focusing scheme		equal focusing in *x*- and *y*-direction
Matching scheme		1/2 cell 1/4 strength, 1/2 cell 3/4 strength

13.3 mm-Wave System

Primary waveguide	rectangular corrugated
Waveguide dimensions	15×20 mm^2
Waveguide mode	HE_{11}
Feedback and outcoupling	via optical beam multiplication in stepped waveguides
Feedback coefficient	adjustable 0–100 %
Output window	Brewster-angle boron-nitride window

13.4 mm-Wave Output Power

mm-wave frequency[1)]	130–260 GHz
On-line tunability[2)]	5% on ms time-scale
Output power	1 MW
Electronic efficiency	5%
System efficiency	> 50%

[1)] Slow frequency tuning by changing the electron beam energy from 1.35 to 2.0 MeV, and adjusting the height of the stepped waveguides (mechanical adjustment).

[2)] Frequency adjustable on ms-time scale, via a sweep of the electron beam energy. The bandwidth of the stepped waveguides is sufficient to sweep over 5%.

Table 38 State-of -the-art of millimeter- and submillimeter-wave FEMs

Institution	Frequency [GHz]	B_w [T]	λ_w [mm]	Mode	Power [MW]	Efficiency [%]	Gain [dB]	Voltage [MV]	Current [kA]	Accelerator	Pulse-Length [µs]	Type
CEA/CESTA, LeBarp	3	0.11	120	TE_{11}^c	40	2.3		2.2	0.8	Ind. LINAC	0.025	spon.emiss.
[1386–1397]	8.6	0.45	20 (grating)	TEM_{00} (2nd harm.)	0.02	0.15		0.085	0.15	Pulse Line	0.25	Smith-Purcell
	33-36	0.3	80	TE_{11}^c	50	7.1(0.06)	43	1.75	0.4(50)	Pulse Line	0.01	amplifier
	35	0.11/017	120/200	TE_{11}^c	80/150	4.5(3.7)/2.8(0.75)	39/45	2.2/6.7	0.8(1.0)	Ind. LINAC	0.01(0.05)	amplifier
CESTA, AES Princeton	15/30	0.5	6 (grating)	2nd harm.	0.7/0.01	19/0.3		0.08	0.045	Pulse Line	0.2	Smith-Purcell
[1397–1399]	100/200	0.5	0.9 (grating)	1st/2nd harm.	0.0025/10^{-4}	0.08/0.003		0.08	0.04	Pulse Line	0.2	Smith-Purcell
Columbia U. NY	24	0.05/0.04	34/23	TE_{11}^c/TM_{11}^c	1	3.3	20	0.58	0.1	Pulse Line	0.15	Amplifier
[1400–1402]	150	0.18	17	TE_{11}^c	5	5		0.8	0.12	Pulse Line	0.15	oscillator
DLR, Stuttgart [1403]	100	0.1	20	TE_{02}^c	1	2		0.5	0.15	Pulse Line	0.03	spon.emiss.
ENEA Frascati [1404–1409]	85–150	0.61	25	TE_{01}^r	0.003	0.0033		2.3	0.004	Microtron	5.5	oscillator
EP Palaiseau [1410]	120	0.03	20	TE_{11}^c	11.5	6.4		0.6	0.3	Electrostatic	0.02	superrad.
FOM Nieuwegein	206	0.2/0.16	40	HE_{11}^r	0.73 (0.5)	5.7 (3.9)		1.77	0.0072	Electrostatic	0.5 (3.5)	oscillator
[423–433, 1385]	167	0.16	40	HE_{11}^r	0.36 (0.26)	3.1 (2.3)		1.61	0.0071	Electrostatic	0.5(3.0)	oscillator
	169	0.16	40	HE_{11}^r	0.1	0.9 (14 with MDC)		1.60	0.007	Electrostatic	36	oscillator
General Electric	2.6–3.7	0.04	74.2	TE_{01}^r	0.9-1.2	9-10	6-10	0.14–0.17	0.07	Modulator	5.0	amplifer
Microwave Lab.	15.7	0.2	23.6	TE_{01}^r	1.65	6	6	0.23	0.125	Modulator	5.0	amplifier
Palo Alto [421]	54	0.2	3.18	TE_{01}^c	0.15	6	10 (30)	0.07	0.037	Modulator	4.0	amplifier
IEE,China [434]	35	0.31	110		140	5.2	57	3.4	0.95	Ind. LINAC	0.05	amplifier
IAP, Nizhny Novgorod	16.7	0.02		TE_{01}^c	300	11		0.6	4.5	Electrostatic	0.03	oscillator
[1411–1413]	42.8–47.2	0.03	24	TE_{10}^r	7	12(0.5)		0.5	0.12 (3)	Pulse Line	0.015	oscil./CRM
IAP/INP Novosib./KIT[1)] [1414–1441]	75	0.10	40	TEM	100	4.2		0.8	3.0	Pulse Line	1.0	oscillator
IAP/U. Strath./HERC [1442–1444]	28	0.22	16	TE_{11}^c	0.15	0.38		0.2	0.2	Pulse Line	0.0005	superrad.
JINR Dubna/IAP N.Novg.	29.3	0.11	60	TE_{11}^c	6	5 (4)		0.8	0.15 (0.2)	Ind. LINAC	0.2	oscillator
[448, 449, 1445–1465]	30	0.12	60	TE_{11}^c	20 (30)/26	20 (15)	35	0.8	0.13	Ind. LINAC	0.2 (0.1)	oscillator/ampl.
	30.2	0.12	60	TM_{12}^c/TE_{11}^c	15	15 (10)		0.8	0.15 (0.2)	Ind. LINAC	0.2	oscillator
	35	0.19	72	TE_{11}^c	30/23	10		1.5	0.2	Ind. LINAC	0.2	oscillator/ampl.
	59/80	0.1-0.2	36/32	TE_{11}^c	5/5	8-10		0.8/0.9	0.06	Ind. LINAC	0.15/0.15	oscillator

Table 38 (continued)

Institution	Frequency [GHz]	B_w [T]	λ_w [mm]	Mode	Power [MW]	Efficiency [%]	Gain [dB]	Voltage [MV]	Current [kA]	Accelerator	Pulse-Length [μs]	Type
ILE Osaka [1466]	250	0.05	30	TE_{11}^{c}	0.6	0.5	110	0.6	0.2	Ind. LINAC	0.04	amplifier
ILT/ILE Osaka [1467]	60–110	0.71	60	TE_{01}^{r}	0.01	0.2		9.0	0.05	RF LINAC	$4x10^{-6}$	oscillator
ISAS, Sagamihara [1468]	11.8	0.09	32.7	TM_{81}^{c}	3	1		0.43	0.19	Pulse Line	0.4	oscillator
QST2), Ibaraki [1469, 1470]	45	0.18	45	TE_{11}^{c}	6	2.9(0.4)	52	0.82	0.25(2.0)	Ind. LINAC	0.03	amplifier
KAERI, Korea [1471–1473]	27	0.13	32	TM_{11}^{c}	0.001	0.15		0.4	0.0017	Electrostatic	10-30	oscillator
KEK, Tsukuba [1474–1478]	9.4	0.121	160	TE_{01}^{r}	100	12.1(5.1)	21	1.5	0.55(1.3)	Ind. LINAC	0.015	amplifier
LANL, Los Alamos [1479]	11.2/16.4			$TM_{02,\ 03}$	5	0.125		0.8	5.0	Modulator	1.0	oscil./ampl.
LLNL, Livermore [364,	34.6	0.37	98	TE_{01}^{r}	1000	34(7.2)	52	3.5	0.85(4.0)	Ind. LINAC	0.02	amplifier
1480–1485]	140	0.17	98	TE_{11}^{c}	2000	13.3(10)	58	6.0	2.5(3.0)	Ind. LINAC	0.02	amplifier
					500–1000	50 pulses (2-kHz burst)						
MIT, Cambridge	9.3	0.02	33	TE_{11}^{c}	0.1	10	6	0.18	0.0055	Electrostatic	0.02	amplifier
[1122, 1486–1489]	27.5	0.05	30	TE_{11}^{c}	1	10.3(6.3)	–	0.32	0.03(0.05)	Electrostatic	1	oscillator
	33.4	0.15	32	TE_{11}^{c}	61	27	50	0.75	0.3	Pulse Line	0.025	amplifier
	35.2	0.05	30	TE_{11}^{c}	0.8	8.6(5.2)	26	0.31	0.03(0.05)	Electrostatic	1	amplifier
NRL, Washington	13.2-16.6	0.1	25.4	TE_{11}^{c}	4.2	18	29	0.245	0.094	Modulator	1.2	amplifier
D.C. [1490, 1491]	23-31	0.06	40	TE_{01}^{c}	4	3		0.7	0.2	Ind. LINAC	0.035	amplifier
	35	0.14	30	TE_{11}^{c}	17	3.2	50	0.9	0.6	Pulse Line	0.02	amplifier
	75	0.08	30	TE_{11}^{c}	75	6	50	1.25	1.0	Pulse Line	0.02	superrad.
NSWC/MRC, Wash. D.C. [434]	95	0.2	100		10	4		2.5	0.1	Pulse Line	0.25	oscillator
RI, Moscow [1492]	6-25	0.03	48	TE_{11}^{c}/TM_{01}^{c}	10	1.7		0.6	1	Pulse Line	2	spon. emiss.
SIAE, Chengdu [1493]	37	0.125	34.5	TE_{11}^{c}	7.6	5.4		0.5	0.28	Electrostatic	0.015	oscillator
SIOFM, Shanghai	37.5	0.12	21	TE_{11}^{c}	12	3.7	50	0.4	0.8	Pulse Line	0.02	amplifier
[1494, 1495]	39	0.126	22	TM_{01}^{c}	14	4.4		0.4	0.8	Pulse Line	0.02	oscillator
	83-95	0.15	10	TE_{11}^{c}/TM_{01}^{c}	1	0.7		0.35	0.4	Pulse Line	0.02	spon. emiss.
TRW, Redondo	35	0.16	20	TE_{01}^{r}	0.1	9.2		0.3	0.004	Electrostatic	10	oscillator
Beach [1496]	35	0.16	20	TE_{01}^{r}	0.002	6.9	3	0.29	0.0001	Electrostatic	10	amplifier
UESTC, Chengdu [1497, 1498]	90	Smith-Purcell		TEM_{00}	0.03	0.03		0.46	0.2	Pulse Line	0.015	oscillator
UNIV. Liverpool [435]	8–12.4	0.1	30	TE_{10}^{r}	2×10^{-5}	0.9		0.12	1.8×10^{-5}	Electrostatic	CW	oscillator
	9.9	0.017	19	TE_{10}^{r}	10^{-6}	0.2	18	0.05	1×10^{-5}	Electrostatic	CW	amplifier
UNIV. Maryland [1479, 1499, 1500]	35	CHI-wiggl.	64	TE_{01}^{coax}	0.0038	0.018	5	0.0011	0.0019	Electrostatic	1	amplifier

Table 38 (continued)

Institution	Frequency [GHz]	B_w [T]	λ_w [mm]	Mode	Power [MW]	Efficiency [%]	Gain [dB]	Voltage [MV]	Current [kA]	Accelerator	Pulse-Length [µs]	Type
	86	0.38	9.6	TE_{01}^{r}	0.25	3.3	24	0.45	0.017	Pulse Line	0.02	amplifier
UCSB Santa Barbara [367, 368, 1501–1503]	120–880	0.15	71.4		0.027	0.5		2–6	0.002	Electrostatic	1–20	oscillator
UNIV. Strathclyde [1504–1506]	8–16	0.11	45	TE_{11}^{c}	1	5.7 (35 with MDC)	23	0.35	0.050	Pulse Line	0.08	amplifier
UNIV. Strath., IAP / KIT[1)]	32.5	0.13	23	TE_{11}^{c}	0.5	5.0		0.3	0.03	Pulse Line	0.1	oscillator
[1507–1520]	37.3	0.06	40	$TEM/TE_{24,1}$ coaxial 2D-1D Bragg cavity	60	10		0.45	1.35	Pulse Line	0.15	oscillator
UNIV. Tel-Aviv [1521–1526]	4.5	0.03	44.4	TE_{01}^{r}	0.0035	6.3		0.07	0.0008	Electrostatic	3	oscillator
	70–110	0.2	44.4	$HE_{10}^{(\,)}/HE_{11}$	0.01	0.7(0.5)		1.1–1.5	0.001(0.0014)	Electrostatic	10-30000	oscillator
UNIV. Twente [1527]	35	0.19	30	TE_{11}^{c}/TM_{01}^{c}	2.3	0.6		0.5	0.75	Pulse Line	0.1	spon. emiss.

r rectangular waveguide, c circular waveguide

[1)] Formerly, then FZK, [2)] formerly JAERI, then JAEA, now QST

Table 39 Comparison of parameters and features of gyrotrons and FEMs for ECRH

	Gyrotron oscillator (cyclotron resonance maser axial magnetic field)	Free electron maser oscillator (periodic transverse magnetic field)
1. Beam voltage	low (70–95 kV)	high (0.2–2 MV)
2. Magnetic field (140 GHz)	high (5.5, 1st harmonic)	low (0.2 T, wiggler)
3. Frequencies	8–1300 GHz	270 MHz—visible
4. Frequency tunability	$\Delta U_{beam} + \Delta U_{mod}$: fast step tuning (5%) ΔB: slow step tuning (35%)	ΔU_{beam}: fast continous tuning (10%) slow mechanincal tuning (50%)
5. Electron beam	magnetron injection gun	Pierce elctron gun, acceleration and deceleration tubes, beam optics
6. Ohmic losses in cavity	cutoff cavity 2–2.5 kW/cm^2	oversized circuit far away from cutoff
7. Power density in cavity	high	low
8. Longitudinal mode competition in cavity	single-mode operation	nonlinear temporal dynamics can bring broad frequency spectrum
9. Linearly polarized output mode	generated by internal quasi-optical mode converter	linearly polarized, low-order resonator mode
10. Number of internal quasi-optical mirrors	3–5 mostly on 35 kV potential 0.9% ohmic losses	15–25 (FOM FEM) phase coherence required mostly on 2 MW potential 6% ohmic losses
11. Absorbed power on first mirror (1 MW, 140 GHz)	3 kW	12 kW
12. Internal microwave diagnostics	not required	required
13. Output power present status	0.92 MW/1800 s/140 GHz 1.2 MW/100 s/170 GHz 1.0 MW/800 s/170 GHz 0.8 MW/3600 s/170 GHz (coax. 2.2 MW/5 ms/170 GHz)	pulsed 2 GW/20 ns/140 GHz but very low duty cycle (LLNL amplifier) 0.73/500 ns/206 GHz (FOM FEM)
14. Exp. system efficiency without energy recovery	55% 35%	low 5–10%
15. Collector loading	relatively low	high
16. Theor. system efficiency with depressed collector	60 % (exp. 55%)	60 % (exp. 14%)
17. Physical size	3 m × 3 m × 3 m	12 m × 3 m × 3 m
18. Theoretical power/unit	1.5 MW (coax., 4 MW)	5 MW

14 Comparison of Gyrotron and FEM for Nuclear Fusion

Table 39 lists a comparison of the main performance parameters and features of gyrotrons and FEMs for ECRH of plasmas in nuclear fusion research. The important advantage of the FEM is its fast and continuous frequency tunability and the possibility of very high peak power but the gyrotron is a much simpler device [4]. The cylindrical cavity gyrotron is the only mm-wave source which has an extensive on-the-field experience during fusion plasma heating experiments over a wide range of frequencies and power levels (8–170 GHz, 0.1–1.0 MW) [6, 22–28].

15 New Trends in Gyrotron Development

Challenges in the development of future advanced gyrotrons are multi-frequency (multi-purpose) and stepwise frequency tunable tubes (see Tables 4, 5, 6, 7, 8, and 9) with frequencies higher than 200 GHz for ECRH&CD of plasmas in a DEMOnstration fusion reactor (DEMO) and sub-THz gyrotrons for Collective Thomson Scattering (CTS) plasma diagnostics and for very high magnetic field DNP-NMR spectroscopy (see Tables 14, 15, 16, 17, and 18). The unit power may be enlarged to 1.5–2 MW by empoying injection-locked and coaxial-cavity multi-megawatt gyrotrons (see Tables 5 and 6). Efficiency enhancement via multi-stage depressed collectors, frequency stability, fast oscillation recovery methods and reliability, availability, maintainability and inspectability (RAMI) are other important issues [1528].

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Compliance with ethical standards

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