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STATE-OF-THE-ART OF HIGH POWER GYRO-DEVICES AND FREE ELECTRON MASERS UPDATE 1995

Abstract

Gyrotron oscillators are mainly used as high power millimeter wave sources for electron cyclotron resonance heating (ECRH) and diagnostics of magnetically confined plasmas for generation of energy by controlled thermonuclear fusion. 140 GHz (110 GHz) gyrotrons with output power P_{out} = 0.54 MW (0.93 MW), pulse length τ = 3.0 s (2.0 s) and efficiency η = 40 % (38 %) are commercially available. Total efficiencies around 50 % have been achieved using single-stage depressed collectors. Diagnostic gyrotrons deliver P_{out} = 40 kW with τ = 40 μs at frequencies up to 650 GHz ($\eta \geq$ 4 %). Recently, gyrotron oscillators have also been successfully used in materials processing. Such technological applications require gyrotrons with the following parameters: f $\geq$ 24 GHz , P_{out} = 10-50 kW, CW, $\eta \geq$ 30. This paper gives an update of the experimental achievements related to the development of high power gyrotron oscillators for long pulse or CW operation and pulsed diagnostic gyrotrons. In addition, this work gives a short overview of the present development of gyrotrons for technological applications, relativistic gyrotrons, quasi-optical gyrotrons, cyclotron autoresonance masers (CARMs), gyroklystrons, gyro-TWT amplifiers, gyrotwystron amplifiers, gyro-BWO's, gyropeniotrons and free electron masers (FEMs). The most impressive FEM output parameters are: P_{out} = 2GW, τ = 20 ns, η = 13 % at 140 GHz (LLNL) and P_{out} = 15 kW, τ = 20 μs, η = 5 % in the range from 120 to 900 GHz (UCSB).

STATUS DER ENTWICKLUNG VON HOCHLEISTUNGS-GYRO-RÖHREN UND FREI-ELEKTRONEN-MASERN STAND: ENDE 1995

Übersicht

Gyrotronoszillatoren werden vorwiegend als Hochleistungsmillimeterwellenquellen für die Elektron-Zyklotron-Resonanzheizung (ECRH) und Diagnostik von magnetisch eingeschlossenen Plasmen zur Erforschung der Energiegewinnung durch kontrollierte Kernfusion eingesetzt. 140 GHz (110 GHz) Gyrotrons mit einer Ausgangsleistung von P_{out} = 0.54 MW (0.93 MW) bei Pulslängen von τ = 3.0 s (2.0 s) und Wirkungsgraden von η = 40% (38 %) sind kommerziell erhältlich. Durch den Einsatz von Kollektoren mit einstufiger Gegenspannung werden Gesamtwirkungsgrade um 50 % erreicht. Gyrotrons zur Plasmadiagnostik arbeiten bei Frequenzen bis zu 650 GHz bei P_{out} = 40 kW und τ = 40 μs ($\eta \geq$ 4 %). In jüngster Zeit jedoch finden Gyrotronoszillatoren auch bei der Materialprozeßtechnik erfolgreich Verwendung. Dabei werden Röhren mit folgenden Parametern eingesetzt: f $\geq$ 24 GHz, P_{out} = 10-50 kW, CW, $\eta \geq$ 30 %. In diesem Beitrag wird auf den aktuellen experimentellen Stand bei der Entwicklung von Hochleistungs-Gyrotronoszillatoren für Langpuls- und Dauerstrichbetrieb sowie von gepulsten Diagnostikgyrotrons eingegangen. Außerdem wird auch kurz über den neuesten Stand der Entwicklung von Gyrotrons für technologische Anwendungen, relativistischen Gyrotrons, quasi-optischen Gyrotrons, Zyklotron-Autoresonanz-Masern (CARMs), Gyroklystrons, Gyro-TWT-Verstärkern, Gyrotwystron-Verstärker, Gyro-Rückwärtswellenoszillatoren (BWOs), Gyro-Peniotrons und Frei-Elektronen-Maser (FEM) berichtet. FEM-Rekordausgangsparameter sind hier: P_{out} = 2 GW, τ = 20 ns, η = 13 % bei 140 GHz (LLNL) und P_{out} = 15 kW, τ = 20 μs, η = 5 % im Bereich von 120 bis 900 GHz (UCSB).

Contents

1 Introduction

The possible applications of gyrotron oscillators and other cyclotron-resonance maser (CRM) fast wave devices span a wide range of technologies. The plasma physics community has already taken advantage of recent advances in producing high power micro- and millimeter (mm) waves in the areas of RF plasma heating for magnetic confinement fusion studies, such as lower hybrid heating (1-8 GHz) and electron cyclotron resonance heating (28-140 GHz), plasma production for numerous different processes and plasma diagnostic measurements such as collective Thomson scattering or heat pulse propagation experiments. Other applications which await the development of novel high power sources include deep space and specialized satellite communication, high resolution Doppler radar, radar ranging and imaging in atmospheric and planetary science, drivers for next-generation high-gradient linear accelerators, nonlinear spectroscopy, material processing and plasma chemistry.

Most work on CRM devices has investigated the conventional gyrotron oscillator (gyromonotron) [1-4] in which the wave vector of the radiation in an open-ended, irregular cylindrical waveguide cavity is transverse to the direction of the applied magnetic field, resulting in radiation near the electron cyclotron frequency or at one of its harmonics. Long pulse and CW gyrotron oscillators delivering output powers of 100-400 kW at frequencies between 28 and 82.6 GHz have been used very successfully in thermonuclear fusion research for plasma ionization and start-up, electron cyclotron resonance heating (ECRH) and local current density profile control by noninductive electron cyclotron current drive (ECCD) at power levels up to 4 MW.

ECRH has become a well-established heating method for both tokamaks [5] and stellarators [6]. The confining magnetic fields in present day fusion devices are in the range of B_0=1-3.5 Tesla. As fusion machines become larger and operate at higher magnetic fields ($B \cong 5T$) 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 projected tokamak experiment ITER (International Thermonuclear Experimental Reactor) and of the future new stellarator (W7-X) at the Division of the Max-Planck-Institut für Plasmaphysik in Greifswald are between 10 and 50 MW at frequencies between 140 GHz and 170 GHz [7]. This suggests that mm-wave gyrotrons that generate output power of at least 1 MW, CW, per unit 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} Gaussian beam mode. Single mode 110-170 GHz gyromonotrons capable of high average power 0.5 - 1 MW per tube, CW, 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 operation and the appropriate mm-wave vacuum window. 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 [8]. Slow frequency tuning has been shown to be possible on quasi-optical Fabry-Perot cavity gyrotrons [9] as well as on cylindrical cavity gyrotrons with step tuning (different working modes) [10, 11].

This work reports on the status and future prospects of the development of gyrotron oscillators for ECRH but also refers to the development of pulsed very high frequency gyromonotrons for active plasma diagnostics [12].

Recently, gyrotron oscillators also are successfully utilized in materials processing (e.g. advanced ceramic sintering, surface hardening or dielectric coating of metals and alloys) as well as in plasma chemistry [13]. 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. The state-of-the-art in this area is also briefly reviewed here.

The next generation of high-energy physics accelerators and the next frontier in understanding of elementary particles is based on the super collider. For linear electron-positron colliders that will reach center-of-mass energies of about 1 TeV it is thought that sources at 17 to 35 GHz with P_{out} = 300 MW, τ = 0.2 μs and characteristics that will allow approximately 1000 pulses per second will be necessary as drivers [14]. 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 [15]. Therefore this report gives an overview of the present development status of relativistic gyrotrons, cyclotron autoresonance masers (CARM), gyrotron travelling wave tube amplifiers (Gyro-TWT), gyroklystrons and gyrotwystrons for such purposes as well as of free electron masers (FEM) and broadband gyrotron backward wave oscillators (Gyro-BWO) for use as drivers for FEM amplifiers.

The present status report updates the experimental achievments in the development of high power gyro-devices and free electron masers reviewed in the FZKA Report 5564 (April 1995) with the same title.

2 Classification of fast-wave microwave sources

Fast-wave devices in which the phase velocity v_{ph} of the electromagnetic wave is greater than the speed of light c, generate or amplify coherent electromagnetic 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 field is mainly transverse to the propagation direction.

The condition for coherent radiation is that the contribution from the electrons reinforces the original emitted radiation in the oscillator or the incident electromagnetic wave in the amplifier. This condition is satisfied if a bunching mechanism exists to create electron density variations of a size comparable to the wavelength of the imposed electromagnetic wave. To achieve such a mechanism, a resonance condition must be satisfied between the periodic motion of the electrons and the electromagnetic wave in the interaction region [15]

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

here ω and k_z are the electromagnetic wave 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 the electron cyclotron maser (ECM), electromagnetic energy is radiated by relativistic electrons gyrating along an external longitudinal magnetic field. In this case, the effective frequency Ω corresponds to the relativistic electron cyclotron frequency:

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

where e and m_o are the charge and rest mass of an electron, γ is the relativistic factor, and B_o is the magnitude of the guide magnetic field. 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 gyration phase and reinforces the existing wave electric field. The strength of the magnetic field determines the value of the radiation frequency.

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

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

The operating frequency of such devices, an example of which is the FEM [16,17], 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 electromagnetic waves of very short wavelength determined by the relativistic Doppler effect. The bunching of the electrons in FEMs is due to the perturbation of the beam electrons by the ponderomotive potential well which is caused by "beating" of the electromagnetic 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 periodically rippled walls or dielectric loading and can instead use a simple hollow-pipe oversized waveguide as a circuit. These devices are capable of producing very high power radiation at cm-, mm-, and submillimeter wavelengths.

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 [1,18]: Richard Twiss in Australia [19], Jürgen Schneider in the U.S [20] and Andrei Gaponov in Russia [21]. 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 [1,18]. The predominance of the fast-wave ECM resonance with its azimuthal bunching in producing microwaves was experimentally verified in the mid-1960s in the U.S. [22] (where the term "electron cyclotron maser" was apparently coined) and in Russia [23].

Many configurations can be used to produce coherent radiation based on the electron cyclotron maser 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 [24,25], show the region of cyclotron interaction (maximum gain of the instability) between an electromagnetic mode and a fast electron cyclotron mode (fundamental or harmonic) as an intersection of the waveguide mode dispersion curve (hyperbola):

$$\omega^2 = k_z^2 c^2 + k_\perp^2 c^2 \qquad (4)$$

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 n^{th} 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. Increases in device power were the result of Russian developments from the early 1970s in magnetron injection guns, which produce electron beams with the necessary transverse energy (while minimizing the spread in transverse energies) and in tapered, open-ended waveguide cavities that maximize efficiency by tailoring the electric field distribution in the resonator [1-3].

Gyrotron oscillators and gyroklystrons are devices which usually utilize only weakly relativistic electron beams (<100 kV) with high transverse momentum (pitch angle $\alpha = v_\perp/v_z > 1$) [26]. The wavevector of the radiation in the cavity is 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 at one of its harmonics:

$$\omega \cong s\Omega_c \ , \qquad s = 1,2,... \qquad (5)$$

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 $\omega - s\Omega_c$ is small but positive in order to achieve correct phasing, i.e. keeping electron bunches in the retarding phase [24-26]. 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 X_{mn} and oscillating at frequency ω is only excited over a narrow range of B_o. By variation of the magnetic field, a sequence of discrete modes can be excited. The frequency scaling is determined by the value of B_o/γ. Cyclotron harmonic operation reduces the required magnetic field for a given frequency by the factor s. The predicted efficiency for gyrotrons operating at higher harmonics (s = 2 and 3) are comparable with those operating at the fundamental frequency [1-3,24].

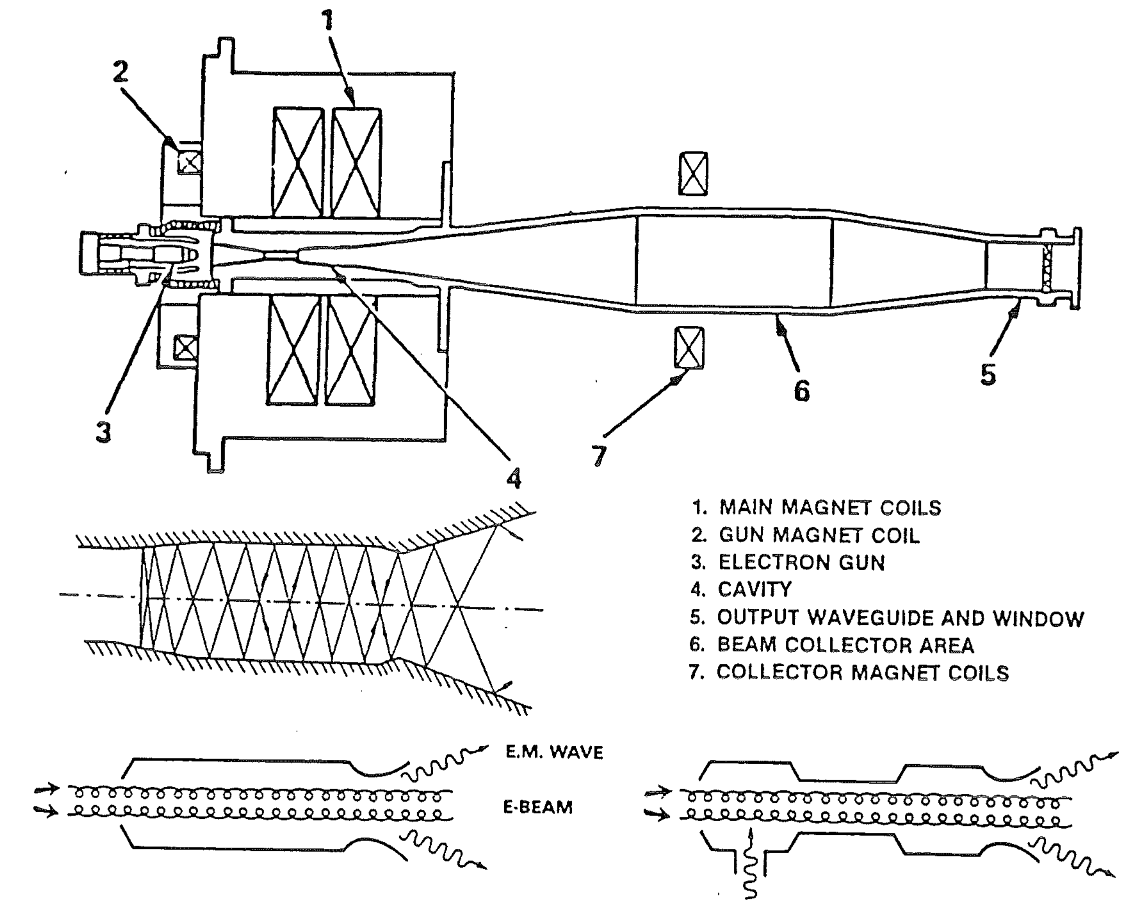


Fig. 1: Schematic of VARIAN CW gyrotron oscillator [4] and scheme of irregular waveguide cavities of gyromonotron oscillator (left) and gyroklystron amplifier [24].

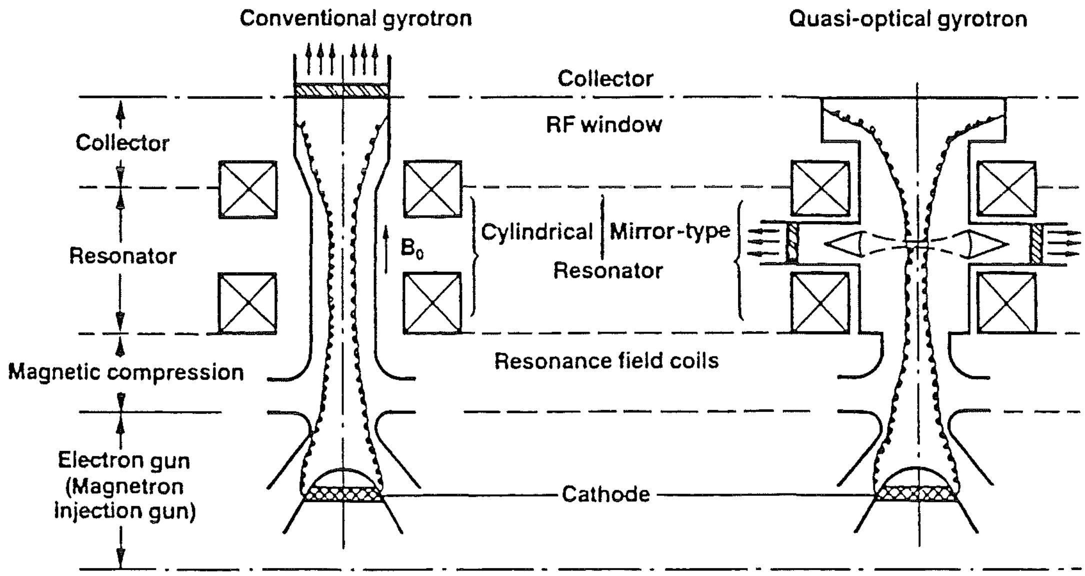


Fig. 2: Principle of a conventional gyrotron with cylindrical resonator and of a quasi-optical gyrotron with mirror resonator [9].

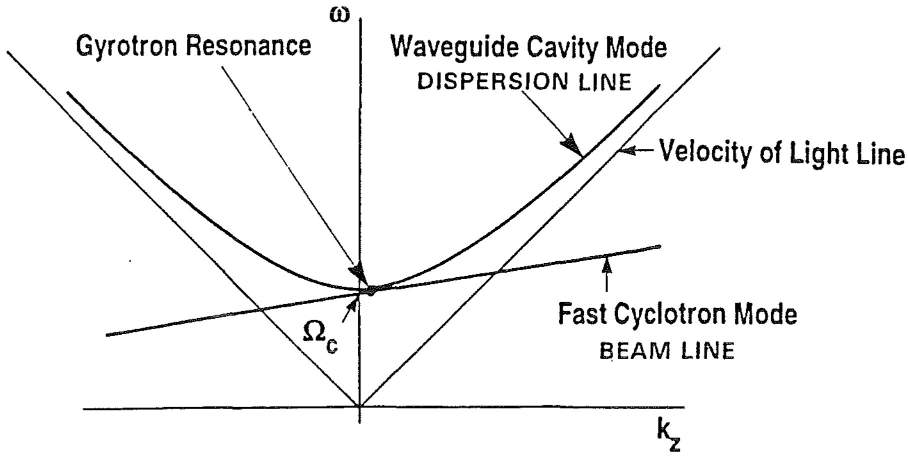


Fig. 3 Dispersion diagram of gyrotron oscillator (fundamental resonance)

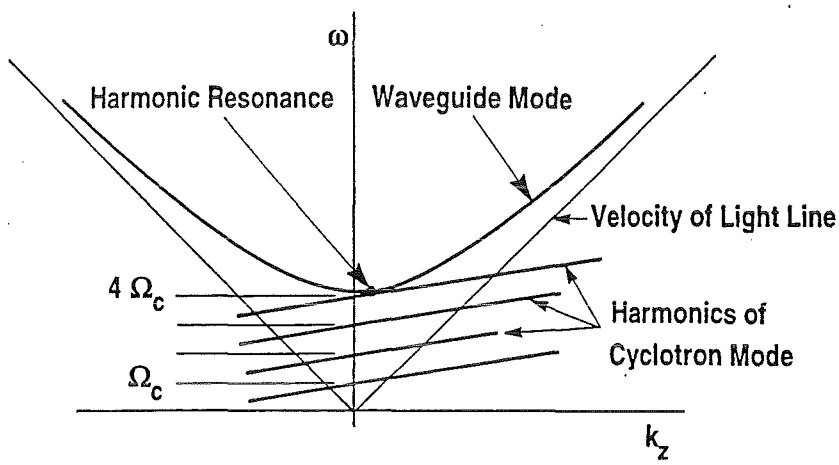


Fig. 4 Dispersion diagram of harmonic frequency gyrotron oscillator

3.2 Cyclotron autoresonance maser (CARM)

In a gyrotron with a highly relativistic beam (≥ 1MeV), an 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 greater than in the mildly relativistic case. It is therefore desirable to identify the condition under which such a highly relativistic electron beam remains in synchronism with the RF field. A possibility for achieving synchronism is to utilize the interaction of electrons with electromagnetic waves propagating with a phase velocity close to the speed of light in the direction of the 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 shifted term. Therefore, if the resonance condition 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 [16]. Fig. 5

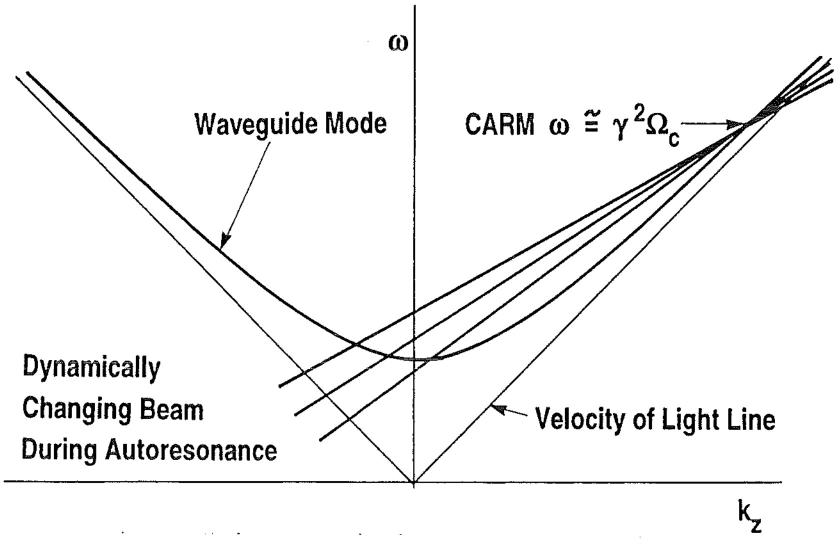


Fig. 5: Dispersion diagram of the cyclotron autoresonance maser (CARM).

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. 6) [16] is required for an oscillator and it is necessary to carefully discriminate against the other interactions corresponding to the lower frequency intersection in the dispersion diagram Fig. 5. The problem can be alleviated by employing the fundamental TE_{11} or (HE_{11} hybrid mode) and properly choosing system parameters to be within the stability limit. Compared to a gyrotron, there is a large Doppler frequency upshift of the output ($\omega \cong \gamma^2\Omega_c$) permitting a considerably reduced magnetic field B_0. Since the axial bunching mechanism can substantially offset the azimuthal bunching the total energy of the beam and not only the transverse component is available for RF conversion.

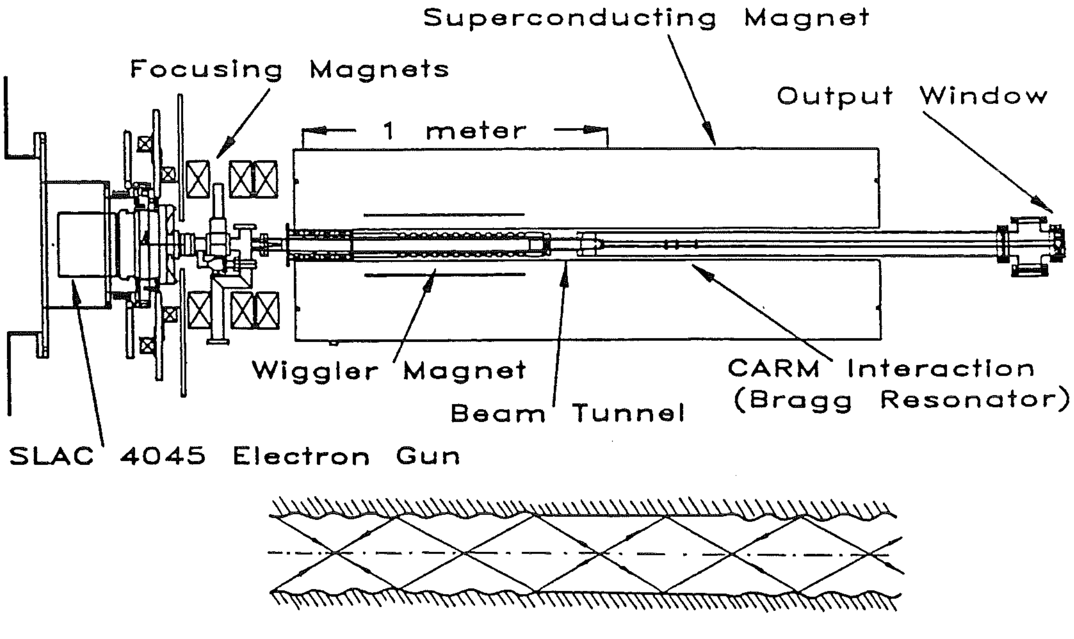


Fig. 6: Schematic of the long-pulse MIT CARM oscillator experiment [27] and scheme of a Bragg resonator [16].

In contrast to the gyrotron the CARM has an electron beam with low to moderate pitch angle ($\alpha < 0.7$). 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%. [16,26].

3.3 Gyro-TWT (travelling wave tube) 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. 7) where the resonance line is tangent to the electromagnetic mode. This produces high gain and efficiency because the phase velocities of the two modes are

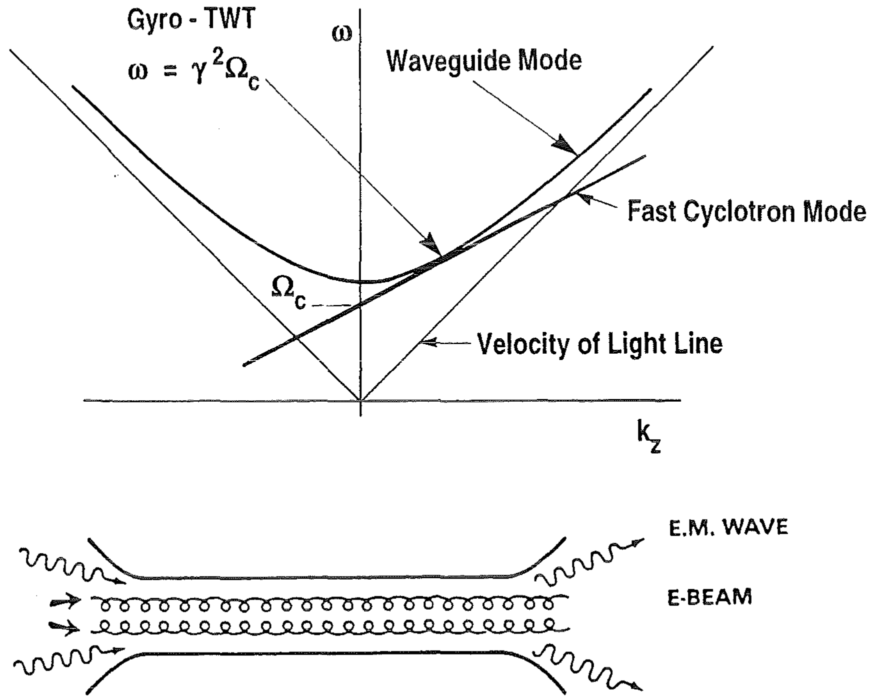


Fig. 7: Dispersion diagram and scheme of interaction circuit of Gyro-TWT amplifier.

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 waveguide. Since no resonant structures are present, the gyro-TWT is potentially capable of much larger bandwidth than a gyroklystron and thus can be used as output amplifier in mm-wave radar communication systems. Recent devices employ tapered magnetic field and interaction circuit as well as two stages in order to optimize the beam-wave interaction along the waveguide [28].

The gyrotwystron [1], a hybrid device, is derived from the gyroklystron by extending the length of the drift section and replacing the output cavity with a sligthly 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 cavity.

3.4 Gyro-BWO (backward wave oscillator)

If the electron beam and/or magnetic field is adjusted so that the straight fast-wave beam line crosses the negative k_z-branch of the waveguide mode hyperbola (see Fig. 8) then an absolute instability (internal feedback) with a "backward wave" occurs. In the gyro-BWO the

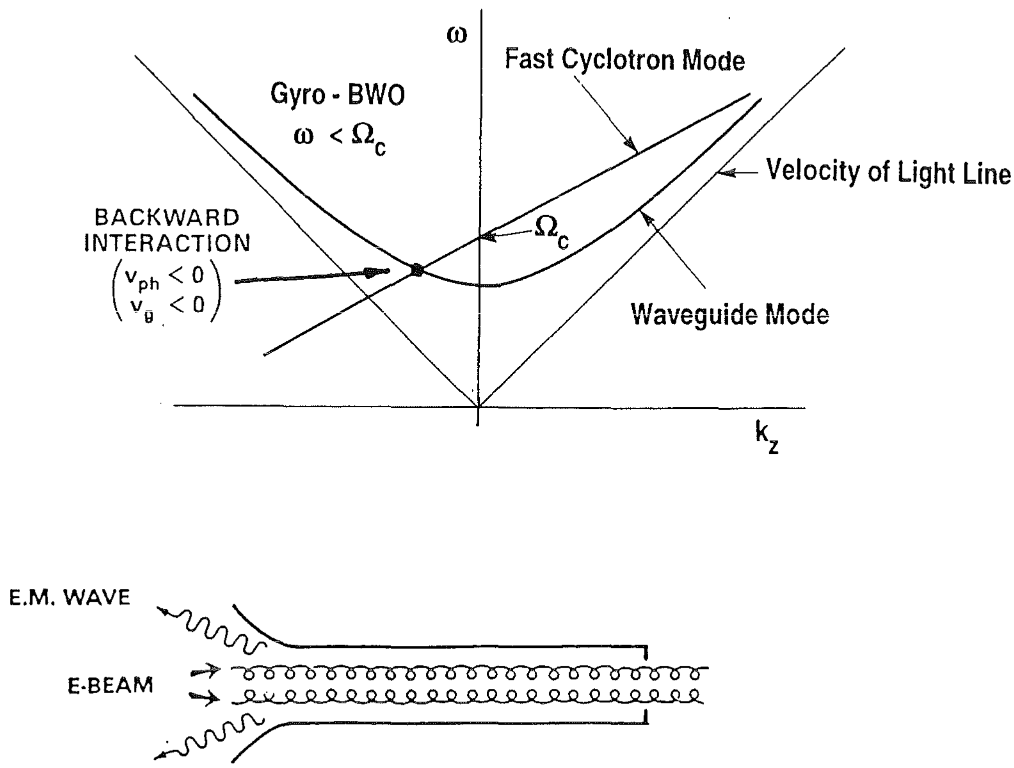


Fig. 8: Dispersion diagram and scheme of interaction circuit of Gyro-BWO.

frequency of operation is now governed by the slope of the line, which is a function of v_z, and thus of the beam acceleration voltage U_{beam}. Consequently, just as in the case of other BWOs (e.g. carcinotron), the frequency of oscillations can be continuously changed very fast over a broad range, using U_{beam} in place of B_0. However, 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.

3.5 Overview on gyro-devices

Bunching of electrons in the gyrotron oscillator discussed in section 3.1 has much in common with that in conventional "O-type" electron beam devices, namely, monotron, klystron, TWT, BWO and twystron [1]. 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 (at the drift section of a klystron-type devices). This analogy suggests the correspondence between O-type devices and various types of gyro-devices. Table I presents the schematic drawings of devices of both classes and the orbital efficiencies calculated using a uniform approximation for the longitudinal structure of the RF field in the gyromonotron (s=1) [1]. For the gyroklystron, the calculation was made in the narrow-gap approximation of the RF field in the input and output cavities. The electrodynamic systems of the gyro-TWT and gyro-BWO, as well as the output section of the gyrotwystron, were assumed to have the form of a uniform waveguide. In all these cases the magnetic field is assumed to be homogeneous.

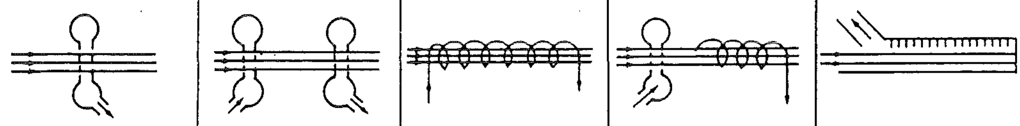
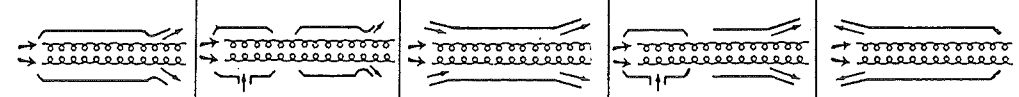
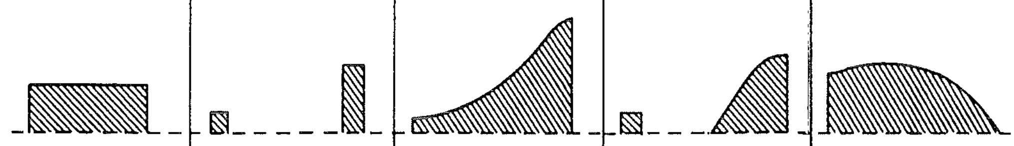
"0" TYPE DEVICE 	MONOTRON	KLYSTRON	TWT	TWYSTRON	BWO
TYPE OF GYROTRON 	GYRO-MONOTRON	GYRO-KLYSTRON	GYRO TWT	GYRO-TWYSTRON	GYRO BWO
RF FIELD STRUCTURE 					
ORBITAL EFFICIENCY	0.42	0.34	0.7	0.6	0.2

Table I: Overview of gyro-devices and comparison with corresponding conventional O-type devices [1].

In Section 10, we will briefly consider two other source types similar to, but also fundamentally different in one way or another from, the ECMs. The large orbit gyrotron employs an axis-encircling electron beam in which the trajectory of each electron takes it around the axis of the cylindrical interaction region. Peniotron and gyropeniotron are driven by an interaction that is phased quite differently from the ECM interaction; in practice, the peniotron and ECM mechanisms compete [24-26].

4 Gyrotron oscillators for plasma heating

Institution		Frequency [GHz]	Mode cavity	Mode output	Power [MW]	Efficiency [%]	Pulse length [s]
ABB, Baden	[29]	8	TE_{01}	TE_{01}	0.35	35	0.5
		39	TE_{02}	TE_{02}	0.25	42	0.1
HUGHES, Torrance	[24]	60	TE_{02}	TE_{02}	0.2	35	0.1
IEAS, Beijing	[30]	34.3 ($2\Omega_c$)	$TE_{02/03}$	TE_{03}	0.2	30	0.02
		36.5 ($2\Omega_c$)	TE_{02}	TE_{02}	0.1	25	0.02
MITSUBISHI, Amagasaki	[31]	88	$TE_{8,2}$	TEM_{00}	0.15	25	0.003
NEC, Kawasaki	[31]	35	TE_{01}	TE_{01}	0.1	30	0.001
NRL,WashingtonD.C.	[24]	35	TE_{01}	TE_{01}	0.15	31	0.02
PHILIPS[1], Hamburg	[32]	70	TE_{02}	TE_{02}	0.14	30	CW
GYCOM (SALUT,IAP)		28	TE_{42}	TEM_{00}	0.5	40	0.2
Nizhny Novgorod		37.5	TE_{62}	TEM_{00}	0.5	35	0.2
[11,33,34]		53.2	TE_{83}	TEM_{00}	0.52	42	0.2
		75	TE_{94}	TEM_{00}	0.5	37	0.2
		82.6	$TE_{10,4}$	TEM_{00}	0.59	38	2.0
					0.9	35	0.3
		82.6	$TE_{15,4}$	TEM_{00}	0.5	37	2.0
THOMSON TE,		8	TE_{51}	TE_{51}	1.0	45	1.0
Velizy	[35]	35	TE_{02}	TE_{02}	0.2	43	0.15
TOSHIBA,		28	TE_{02}	TE_{02}	0.2	35.7	0.075
Nasushiobara	[36]	41	TE_{02}	TE_{02}	0.2	31.3	0.1
		56	TE_{02}	TE_{02}	0.2	32.9	0.1
		70	TE_{02}	TE_{02}	0.025	28.4	0.001
CPI[2],		8	TE_{21}	TE_{10}	0.5	33	1.0
Palo Alto	[4,37]	28	TE_{02}	TE_{02}	0.34	37	CW
					0.2	45	CW
		35	TE_{02}	TE_{02}	0.2	35	CW
		53.2, 56, 60	$TE_{01/02}$	TE_{02}	0.23	37	CW
		70	$TE_{01/02}$	TE_{02}	0.21	36	3
		84	$TE_{15,2}$	$TE_{15,2/4}$	0.5	28	0.1
					0.89	28	0.001
CPI[2], NIFS		84	$TE_{15,3}$	TEM_{00}	0.5	29	2.0
Palo Alto, Nagoya	[38]				0.4	28	10.5
					0.05	14	CW

[1] former VALVO, [2] Communications and Power Industries, former VARIAN

Table II: Performance parameters of gyrotron oscillators for electron cyclotron resonance heating (ECRH) (28-84 GHz) and lower hybrid heating (8 GHz) of plasmas in magnetic confinement fusion studies.

Institution	Frequency [GHz]	Mode cavity	Mode output	Power [MW]	Efficiency [%]	Pulse length [s]
FZK[1)], Karlsruhe [41-43]	117.9	$TE_{19,5}$	TEM_{00}	0.75	23	0.001
				0.75	32(SDC)	0.001
	132.6	$TE_{9,4}$	$TE_{9,4}$	0.42	21	0.005
MITSUBISHI,	120	$TE_{02/03}$	TE_{03}	0.16	25	0.06
Amagasaki [44,45]	120	$TE_{15,2}$	$TE_{15,2}$	1.02	32.5	0.0002
				0.46	30	0.1
				0.25	30	0.21
GYCOM (SALUT, IAP)	106.4	$TE_{15,4}$	TEM_{00}	0.55	33	0.2
Nizhny Novgorod [11,33]	110	$TE_{15,4}$	TEM_{00}	0.5	33	0.5
GYCOM (TORIY, IAP)	110	$TE_{19,5}$	TEM_{00}	1.2	40	0.0002
Moscow, N.Novgorod [52]				0.93	38	2.0
THOMSON, Velizy [35]	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
THOMSON, CEA, CRPP, FZK	118	$TE_{22,6}$	TEM_{00}	0.7	37	0.001
[53]				0.5	31	2.0
TOSHIBA, JAERI	110	$TE_{22,2}$	TEM_{00}	0.75	27.6	0.002
Nasushiobara, Naka [46-48]				0.61	30	0.05
				0.61	50(SDC)	0.05
				0.42	48(SDC)	3.3
				0.35	48(SDC)	5.0
	110.1	$TE_{22,6}$	$TE_{22,6}$	0.66	31.5	0.001
	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
CPI[2)],	106.4 ($2\Omega_c$)	$TE_{02/03}$	TE_{03}	0.135	21	0.1
Palo Alto [4,37,53-55]	106.4	$TE_{12,2}$	$TE_{12,2}$	0.4	30	0.1
	110	$TE_{15,2}$	$TE_{15,2}$	0.5	28	1.0
				0.3	28	2.0
	110	$TE_{22,2}$	$TE_{22,2/4}$	0.5	27	2.5
	110	$TE_{22,6}$	TEM_{00}	1.0	32	0.001
				0.68	31	0.5
				0.53	30	2.0
				0.4	28	6.5
				0.35	26.5	10.0

SDC: Single-stage Depressed Collector
[1)] former KfK, [2)] Communications and Power Industry, former VARIAN

Table IIIa: Present development status of high frequency gyrotron oscillators for ECRH and stability control in magnetic fusion devices (110 GHz $\leq$ f $<$ 140 GHz, $\tau \geq 0.2$ ms).

Institution	Frequency [GHz]	Mode cavity	Mode output	Power [MW]	Efficiency [%]	Pulse length [s]
FZK[1], PHILIPS[2], [40]	140.8	TE_{03}	TE_{03}	0.12	26	0.5
FZK, Karlsruhe [41-43]	140.2	$TE_{10,4}$	$TE_{10,4}$	0.69	28	0.005
	140.2	$TE_{10,4}$	TEM_{00}	0.60	27	0.012
				0.50	32	0.03
				0.50	48(SDC)	0.03
	140.5	$TE_{10,4}$	TEM_{00}	0.46	51(SDC)	0.2
	147.4	$TE_{11,4}$	$TE_{11,4}$	0.35	19	0.005
	154.8	$TE_{12,4}$	TEM_{00}	0.35	18	0.01
				0.35	27(SDC)	0.005
	140.1	$TE_{22,6}$	TEM_{00}	0.94	22	0.010
	140.1	$TE_{22,6}$	TEM_{00}	0.83	24	0.010
				0.83	37(SDC)	0.010
	162.3	$TE_{25,7}$	TEM_{00}	0.97	26	0.001
				0.97	36(SDC)	0.001
GYCOM (SALUT, IAP)	140	$TE_{22,6}$	TEM_{00}	0.85	36	0.4
Nizhny Novgorod [11,33,34]				0.5	33	2.0
	158.5	$TE_{24,7}$	TEM_{00}	0.7	30	0.7
GYCOM (TORIY, IAP)	140	$TE_{22,6}$	TEM_{00}	0.97	34	0.3
Moscow, N.Novgorod				0.735	40	1.5
[34,48-50]				0.535	40	3.0
TOSHIBA, JAERI	170	$TE_{22,6}$	TEM_{00}	0.45	19	0.05
Nasushiobara,Naka[46-48]				0.25	19	0.4
				0.25	32(SDC)	0.4
	170	$TE_{31,8}$	$TE_{31,8}$	1.1	28	0.0004
CPI[3],	140	$TE_{02/03}$	TE_{03}	0.1	27	CW
Palo Alto [4,37,54]	140	$TE_{15,2}$	$TE_{15,2}$	1.04	38	0.0005
				0.32	30	3.6
				0.26	28	5.0
				0.2 (0.4)	28	avg. (peak)

SDC: Single-stage Depressed Collector
[1] former KfK, [2] former VALVO, [3] Communications and Power Industry, former VARIAN

Table IIIb: Present development status of high frequency gyrotron oscillators for ECRH and stability control in magnetic fusion devices ($f \geq 140$ GHz, $\tau \geq 0.2$ ms).

Institution	Frequency [GHz]	Mode cavity	Mode output	Power [MW]	Efficiency [%]	Corrug. Cavity inner	Corrug. Cavity outer
FZK[1)] Karlsruhe [60]	139.96	$TE_{28,16}$	$TE_{28,16}$	1.14	27.4	yes	no
	142.05	$TE_{29,16}$	$TE_{29,16}$	0.95	24.0	yes	no
IAP, Nizhny Novgorod [3,34,61]	45	$TE_{15,1}$	$TE_{15,1}$	1.25	43	no	no
	100	$TE_{21,18}$	$TE_{21,18}$	1.0	35	yes	no
				0.5	20	no	no
	100	$TE_{25,13}$	$TE_{25,13}$	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
	110	$TE_{17,7}$	$TE_{17,7}$	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
	224($2\Omega_c$)	$TE_{33,8}$	$TE_{33,8}$	0.1	11	yes	no
IAP, FZK[1)] Karlsruhe [60]	133	$TE_{27,15}$	$TE_{27,15}$	1.3	29	no	no
	140	$TE_{28,16}$	$TE_{28,16}$	1.0	23	no	no
MIT, Cambridge [62]	136	$TE_{25,11}$	TEM_{00}	0.51	8	no	no
	140	$TE_{26,11}$	TEM_{00}	0.95	15	no	no
	143	$TE_{27,11}$	TEM_{00}	1.0	16	no	no

[1)] former KfK

Table IV: Present experimental development status of short pulse (3-150 μs) coaxial cavity gyrotron oscillators.

Institution	Frequency [GHz]	Mode cavity	Mode output	Power [MW]	Efficiency [%]	Pulse length [s]
FZK[1)], Karlsruhe [41-43]	117.8	$TE_{19,5}$	TEM_{00}	0.75	23	0.001
				0.75	32 (SDC)	0.001
	140.2	$TE_{10,4}$	TEM_{00}	0.60	27	0.012
				0.50	32	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}	0.83	24	0.010
				0.83	37(SDC)	0.010
	154.8	$TE_{12,4}$	TEM_{00}	0.35	18	0.01
				0.35	27(SDC)	0.005
	162.2	$TE_{25,7}$	TEM_{00}	0.96	26	0.001
				0.96	36 (SDC)	0.001
NRL, Washington D.C. [69]	115	QOG	TEM_{00}	0.60	9	10^{-5}
				0.43	12.7(SDC)	10^{-5}
				0.20	16.1(SDC)	10^{-5}
TOSHIBA, JAERI	110	$TE_{22,2}$	TEM_{00}	0.75	27.6	0.002
Nasushiobara, Naka [46-48]				0.61	30	0.05
				0.61	50(SDC)	0.05
				0.42	48(SDC)	2.6
				0.35	48(SDC)	5.0
	170	$TE_{22,6}$	TEM_{00}	0.45	19	0.05
				0.25	19	0.4
				0.25	32 (SDC)	0.4

SDC: Single-stage Depressed Collector; QOG: Quasi-Optical Gyrotron

1) former KfK

Table V: Present development status of high frequency gyrotron oscillators with single-stage depressed collector (DEPCOL).

50 MW Output Plant	**Power Supply Capacity**	**Cooling System Capacity**	**High-Power Fine Regulation**
Ordinary Gyrotron (η = 35 %)	171 MW	121 MW	required
DEPCOL Gyrotron (η = 50 %)	109 MW	59 MW	not required
Gain Factor	1.57	2.05	

Table VI: Power supply and cooling system capacities required for a 50 MW output plant (at the plasma torus) with ordinary gyrotrons and gyrotrons with depressed collector.

Material	**Type**	**Power (kW)**	**Frequency (GHz)**	**Pulse Length (s)**	**Institution**
water-free fused silica	single disk water edge cooled	200	60	5.0	UKAEA/Culham
boron nitride	single disk water edge cooled	900 550 600	110 140 140	2.0 3.0 2.0	GYCOM (TORIY) GYCOM (TORIY) GYCOM (SALUT)
sapphire	single disk LN_2 edge cooled	500 285* 500 370	118 140 140 140	2.0 3.0 0.5 1.3	CEA/CRPP/FZK/ THOMSON IAP/INFK FZK/IAP/IPF/IPP FZK/IAP/IPF/IPP
sapphire	single disk with Cu anchor LHe edge cooled	410	110	1.0	JAERI/TOSHIBA
sapphire	double disk FC75 face cooled	200 400 350 350 200	60 84 110 110 140	CW 10.5 10.0 5.0 CW	CPI NIFS/CPI CPI JAERI/TOSHIBA CPI
sapphire	distributed water cooled	65** 200*	110 110	0.3 0.7	GA/JAERI/ TOSHIBA GA/CPI

Power densities required for 1 MW-level (*) and 0.8 MW-level (**) gyrotrons (HE_{11})

Tab. VII: Experimental parameters of high-power millimeter-wave vacuum windows.

	140 GHz	**170 GHz**	**220 GHz**
Gaussian Profile (G)	0.5 MW	0.4 MW	0.3 MW
Flattened Profile (F)	0.7 MW	0.6 MW	0.45 MW
Annular Profile (A)	1.0 MW	0.85 MW	0.65 MW

Table VIII: Maximum power transmittance of a single disk, LN_2 edge-cooled sapphire window with resonant thickness ($5\lambda/2$ at 140 GHz, $6\lambda/2$ at 170 GHz, $8\lambda/2$ at 220 GHz) for different power distributions.

	Material	Type	RF-Profile	Cross-Section	Cooling
①	**Sapphire/Metal**	**distributed**	**flattened Gaussian**	**rectangular (100 mm x 100 mm)**	**internally water cooled (300 K)** **$\tan\delta = 2\text{-}5 \cdot 10^{-4}$, k = 40 W/mK**
②	**Diamond**	**single-disk**	**Gaussian**	**rectangular (200 mm x 50 mm)**	**water edge cooled (300 K)** **$\tan\delta = 3.5 \cdot 10^{-5}$, k = 900 W/mK**
			flattened Gaussian	**circular (∅ = 100 mm)**	
③	**Diamond**	**single-disk Brewster**	**Gaussian**	**rectangular (680 mm x 12 mm)**	**water edge cooled (300 K)** **$\tan\delta = 3.5 \cdot 10^{-5}$, k = 900 W/mK**
④	**Silicon Au-doped**	**single-disk**	**flattened Gaussian**	**circular (∅ = 100 mm)**	**edge cooled (200 K),** **cryo-cooler (CHF_3, CF_3Cl)** **$\tan\delta = 3 \cdot 10^{-6}$, k = 250 W/mK**
⑤	**Silicon Au-doped**	**single-disk**	**Gaussian**	**circular (∅ = 100 mm)**	**LN_2 edge cooled (77 K)** **$\tan\delta = 4 \cdot 10^{-6}$, k = 1500 W/mK**
⑥	**Sapphire**	**single disk**	**flattened Gaussian**	**rectangular (285 mm x 35 mm)**	**LN_2 edge cooled (77 K)** **$\tan\delta = 6.7 \cdot 10^{-6}$, k = 1000 W/mK**
⑦	**Sapphire**	**single disk**	**Gaussian**	**circular (∅ = 100 mm)**	**LNe or LHe edge cooled (27 K)** **$\tan\delta = 1.9 \cdot 10^{-6}$, k = 2000 W/mK**

The power capability of options ⑤ and ⑦ is even 1-2 MW, CW at 170 GHz.

Table IX: Options for 1 MW, CW, 170 GHz gyrotron windows.

5 Very high frequency gyrotron oscillators

Institution	Frequency [GHz]	Mode	Power [kW]	Efficiency [%]	Pulse length [ms]
IAP, N.Novgorod [12,84]	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 [83,90]	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
UNIVERSITY, Fukui [85-87]	383	TE_{26}	3	3.7	1
	402	TE_{55}	2	3	1
	576	TE_{26}	1	2.5	0.5

Table X: Capabilities and performance parameters of mm- and submillimeter-wave gyrotrons operating at the second harmonic of the electron cyclotron frequency, with output power $\geq$ 1 kW.

Institution	Frequency [GHz]	Mode	Power [MW]	Efficiency [%]	Pulse length [μs]
MIT, Cambridge [10,82,83]	113.2	$TE_{23,6}$	0.84	25	3
	113.2	$TE_{23,6}/TEM_{00}$	0.84	17	3
	140	$TE_{15,2}$	1.33	40	3
	148	$TE_{16,2}$	1.3	39	3
	166.6	$TE_{27,8}$	1.25	35	3
	170.0	$TE_{28,8}$	0.82	30	3
	173.4	$TE_{29,8}$	0.72	27	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
	|	|	|		|
	287	$TE_{28,4}$	0.2		3
	280	$TE_{25,13}$	0.78	17	3
	267	$TE_{22,5}$	0.537	19	3
	|	|	|		|
	320	$TE_{29,5}$	0.4	20	3
	327	$TE_{27,6}$	0.375	13	3
IAP, Nizhny Novgorod [12]	250	$TE_{20,2}$	0.3	31	30 - 80
	350		0.13	17	30 - 80
	430		0.08	10	30 - 80
	500	$TE_{28,3}$	0.1	8.2	30 - 80
	540		0.06	6	30 - 80
	600	$TE_{38,2}$	0.05	5	30 - 80
	650		0.04	4	40
UNIVERSITY, Fukui [86]	278	TE_{33}	0.001	5	1000
	290	TE_{62}	0.001	4	1000
	314	TE_{43}	0.001	4	1000

Table XI: Capabilities and performance parameters of pulsed millimeter- and submillimeter-wave gyrotron oscillators operating at the fundamental electron cyclotron resonance.

Institution	Frequency [GHz]	Mode	Voltage [kV]	Current [A]	Power [MW]	Efficiency [%]
MIT, Cambridge [58]	187.7	$TE_{32,4}$	94	57	0.65	12
	201.6	$TE_{35,4}$	97	54	0.92	18
	209.5	$TE_{33,5}$	98	37	0.54	15
	213.9	$TE_{34,5}$	95	51	0.89	18
	218.4	$TE_{35,5}$	90	44	0.56	14
	224.3	$TE_{33,6}$	91	60	0.90	17
	228.8	$TE_{34,6}$	92	59	0.97	18
			100	59	1.2	20
	265.7	$TE_{39,7}$	90	57	0.64	12
	283.7	$TE_{43,7}$	92	35	0.33	10
	291.6	$TE_{41,8}$	93	54	0.887	18

Table XII: Step tuning of MIT gyrotron oscillator (with large MIG [58]) operating at the fundamental electron cyclotron resonance (pulse length 1.5 μs).

Institution	Frequency [GHz]	Mode	Voltage [kV]	Current [A]	Power [MW]	Efficiency [%]
MIT, Cambridge [58]	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	0.66	14
	292.9	$TE_{25,14}$	95	41	0.72	18
	302.7	$TE_{27,14}$	96	43	0.27	7

Table XIII: Step tuning of MIT gyrotron oscillator (with small MIG [58]) operating at the fundamental electron cyclotron resonance (pulse length 1.5 μs).

6 Gyrotrons for technological applications

Institution	Frequency [GHz]	Mode cavity	Mode output	Power [kW]	Efficiency [%]	Voltage [kV]	
IAP, SALUT,	15	TE_{01}	TE_{01}	4	50	15	
Nizhny Novgorod,	30 ($2\Omega_c$)	TE_{02}	TE_{02}	15	30	22	
TORIY, Moscow	31.8-34.8	TE_{11}	TE_{11}	1.2	40	12	mech.tun.
[11,13,34,49,50]	35.5-37.5	TE_{01}	TE_{01}	0.5	15.3	16	mech.tun.
	37.5	TE_{62}	TEM_{00}	20	35	20	
	78	TE_{32}	TE_{11}	10	30	30	
	83	$TE_{11,3}$	TEM_{00}	20	30	20	
	150	TE_{03}	TE_{03}	22	30	40	
	160 ($2\Omega_c$)	TE_{03}	TE_{03}	2.4	9.5	18	
MITSUBISHI, Amagasaki [103,105]	28 ($2\Omega_c$)	TE_{02}	TE_{02}	10	30.8	25	perm.mag.
CPI[1], Palo Alto [4]	28	TE_{02}	TE_{02}	15	40	40	
CPI, NIFS Palo Alto, Nagoya [38]	84	$TE_{15,3}$	TEM_{00}	50	14	80	

[1] Communications and Power Industry, former VARIAN

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

7 Relativistic gyrotrons

Institution	Frequency [GHz]	Mode	Voltage [MV]	Current [kA]	Power [MW]	Efficiency [%]	
IAP, Nizhny Novgorod	20	TM_{01}	0.5	0.7	40	11.4	
[98]	79-107	TM_{1n}	0.5	2-6.5	30	3-1	slotted echelette cavity, n = 3 - 10
IAP, Nizhny Novgorod	10	TE_{13}	0.3	0.4	25	20	slotted cavity
Lebedev/General Phys. Inst. Moscow [95-98]	10	TE_{13}	0.3	1.0	60	15	slotted cavity with plasma
	40	TE_{13}	0.4	1.3	25	5	slotted cavity
UNIV. Michigan [102]	3	$TE_{10}{}^{r}/TE_{01}{}^{r}$	0.75	0.5(2.0)	5	1.3(0.4)	
	10	TE_{11}	0.4	0.025	0.6	6	
NRL, Washington D.C.	8.35-13		3.3	80	1000	0.4	4-5 modes
[93,99,100]	35	TE_{62}	0.6	2.0	100	8	
			1.15	2.5	275	10	
	35	TE_{13}	0.9	0.65	35	6	slotted cavity
Tomsk Polytech. Inst. [94]	3.1		0.75	8.0(30)	1800	8	also viractor interaction
UNIV. Strathclyde [101]	100		0.2	0.22	6.3	14	

r: rectangular waveguide

Table XV: Present development status of relativistic gyrotron oscillators.

8 Quasi-optical gyrotrons

Institution		Frequency [GHz]	Mode resonator	Power [kW]	Efficiency [%]	Pulse length [ms]
ABB, Baden	[29]	92	TEM_{00q}	90	10	10
CRPP, Lausanne	[9]	90.8	TEM_{00q}	150	15	5
		100	TEM_{00q}	90	11	15
		200($2\Omega_c$)	TEM_{00q}	8	3.5	15
NRL, Washington D.C.	[69,106]	110	TEM_{00q}	80	8	0.013
		115	TEM_{00q}	431	12.7(SDC)	0.013
				197	16.1(SDC)	0.013
		120	TEM_{00q}	600	9	0.013
				200	12	0.013
TOSHIBA,	[36]	112	TEM_{00q}	100	12	5
Nasushiobara		120	TEM_{00q}	26	10(DEB)	3

SDC: Single-stage Depressed Collector
DEB: Dual Electron Beam (1 annular beam, 1 pencil beam)

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

9 Cyclotron autoresonance masers (CARMs)

Institution	Frequency [GHz]	Mode	Power [MW]	Efficiency [%]	Gain [dB]	B-Field [T]	Voltage [MV]	Current [kA]	Type
IAP	35.7	TE_{51}	25	10	-	1.12	0.4	0.6	oscil.
IAP, IHCE	37.5	TE_{11}	10	4	30	0.5	0.5	0.5	ampl.
IAP	38	TE_{11}	13	27(0.65)		1.24	0.5	0.1(4)	oscil.
IAP,IHCE,JINR	50	TE_{11}	30	10	-	0.7	1.0	0.3	oscil.
IAP	66.7	TE_{21}	15	3	-	0.6	0.5	1.0	oscil.
IAP,IHCE,JINR	68	TE_{11}	50	8	-	1.0	1.2	0.5	oscil.
IAP	69.8	TE_{11}	6	4	-	0.6	0.35	0.4	oscil.
IAP [108-111]	125	TE_{41}	10	2	-	0.9	0.5	1.0	oscil.
LLNL Livermore[112]	220	TE_{11}	50	2.5	-	3.0	2.0	1.0	oscil.
MIT Cambridge	27.8	TE_{11}	1.9	5.3	-	0.6	0.45	0.080	oscil.
[27,113,114]	30	TE_{11}	0.1	3	-	0.64	0.3	0.012	oscil.
	32	TE_{11}	0.11	2.3	-	0.63	0.32	0.015	oscil.
	35	TE_{11}	10	3	45	0.7	1.5	0.25	ampl.
UNIV. Michigan [115]	15	TE_{11}	7	1.5	-	0.45	0.4	1.2	oscil.
UNIV. Strathclyde [116]	14.3($2\Omega_c$)	TE_{21}	0.2	4(2)	-	0.2	0.3	0.01(0.02)	oscil.

IAP Nizhny Novgorod, IHCE Tomsk, JINR Dubna

Table XVII: State-of-the-art of CARM experiments (short pulse).

10 Gyroklystrons, gyro-TWT's, gyrotwystrons, gyro-BWOs and other gyro-devices

Weakly Relativistic Pulse Gyroklystrons

Institution	Frequency [GHz]	Mode	No. of cavities	Power [kW]	Efficiency [%]	Gain [dB]	BW [%]	
NRL, Washington D.C.	4.5	TE_{10}	3	70	40	36		
[24,69,117,118]	85	TE_{13}	2	50		20		
	85.5	TEM_{00}	2	82	19	18		QOGK
				82	30 (SDC)	18		QOGK
IAP Nizhny Novgorod	9.25	TE_{01}	2	4	50	22	2.0	
[122-126]			3	3	45	30	2.0	max. power
			3	2	55	15	2.0	max. efficiency
	15.2	TE_{01}	3	50	50	30	1.0	
	15.8	TE_{02}	3	160	40	30	1.0	max. efficiency
	35.12($2\Omega_c$)	TE_{02}	2	205	15	16	0.2	tapered B-field
TORIY, Moscow	35.2	TE_{02}	2	750	24	20	1.2	max. power
[122-124]			2	350	32	19	1.8	max. efficiency
	35.0	TE_{01}	4	160	48	42	2.8	
			3	230	33	31	2.8	
IAP Nizhny Novgorod	93.2	TE_{01}	4	65	26	35	0.6	max. power
[127]			4	57	34	40	0.6	max. efficiency
CPI[1), Palo Alto [24]	10	TE_{01}	3	20	8.2	10	0.4	
	28	$TE_{01/02}$	2	76	9	30	0.4	

QOGK: Quasi-Optical Gyroklystron; SDC: Single-stage Depressed Collector
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Weakly Relativistic CW Gyroklystrons

IAP Nizhny Novgorod	9.17	TE_{11}	2	0.7	70	22	0.6
[125-127]	91.6	TE_{01}	4	2.5	26	31	0.7

Table XVIIIa: Weakly relativistic gyroklystron experimental results

Institution	Frequency [GHz]	Mode	No. of cavities	Power [MW]	Efficiency [%]	Gain [dB]	BW [%]	
UNIV. MARYLAND	9.87	TE_{01}	2	24	32	34	0.25	
[119-121]	9.87	TE_{01}	3	27	32	37	0.2	max. power
			3	16	37	33	0.2	max. efficiency
			3	20	28	50	0.2	max. gain
	19.75 ($2\Omega_c$)	TE_{02}	2	32	28	27	0.15	
	29.63 ($3\Omega_c$)	TE_{03}	2	1	1.2	18	0.1	

Relativistic Pulsed Gyroklystrons

Table XVIIIb: Relativistic pulse gyroklystron experimental results.

Weakly Relativistic Pulse Gyro-TWTs

Institution	Frequency [GHz]	Mode	Power [kW]	Efficiency [%]	Gain [dB]	Bandwidth [%]	
UC LOS ANGELES	10	TE_{10}	55	11	27	11	diel.coat.waveg.
[130,131]	15.7 ($2\Omega_c$)	TE_{21}	207	12.9	16	2.1	slotted waveg.
	16.2 ($8\Omega_c$)	TE_{82}	0.5	1.3	10	4.3	axis-encirl. beam
UNIV. HSINCHU	35.8	TE_{11}	18.4	18.6	18	10	
[132,133]	35.8	TE_{11}	27	16	35	7	2-stage severed
	34.2	TE_{11}	62	21	33	12	2-stage lossy
NRL, Washington D.C.	32.5	TE_{10}	6.3	10	16.7	33	
[24,134-136]	32.5	TE_{10}	8	16	25	20	2-stage
	32.8	TE_{10}	2.5	10			folded waveg.
	34.3	TE_{01}	16.6	7.8	20	1.4	
CPI[1)], Palo Alto[24]	5.18	TE_{11}	128	26	20	7.3	
	95	TE_{11}	15	6.3	30	1.6	

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Relativistic Pulse Gyro-TWTs

Institution	Frequency [GHz]	Mode	Power [MW]	Efficiency [%]	Gain [dB]	Bandwidth [%]
NRL, Washington D.C. [137]	35	TE_{11}	20	11	30	

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

Institution	Frequency [GHz]	Mode cavity	Mode output w.g.	Power [MW]	Efficiency [%]	Gain [dB]	BW [%]
NRL,Washington,D.C. [128]	4.5	TE_{10}	TE_{10}	0.0073	22.5	30	2.5
UNIV. MARYLAND	9.87	TE_{01}	TE_{01}	21.6	22	25.5	2.3
[129]	19.76	TE_{01}(9.88 GHz)	$TE_{02}(2\Omega_c)$	12	11	22	2.3

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

Weakly Relativistic Pulse Gyro-BWOs

Institution		Frequency [GHz]	Mode	Power [kW]	Efficiency [%]	Bandwidth [%]	
NRL, Washington D.C.	[138]	27.8	$TE_{10}{}^{r}$	2	9	3	electr. tuning
		29.2	$TE_{10}{}^{r}$	6	15	13	magn. tuning
UNIV. HSINCHU	[139]	34	$TE_{11}{}^{c}$	20-67	6.5-21.7	5	
				113	19	1	
MIT,Cambr.,LLNL,Liverm.	[140]	140	$TE_{12}{}^{c}$	2	2	9	

r: rectangular waveguide; c: circular waveguide

Relativistic Pulse Gyro-BWOs

Institution	Frequency [GHz]	Mode	Power [MW]	Efficiency [%]	Bandwidth [%]
UNIV. MICHIGAN [141]	4.5-6	TE_{11}	70	3	1
USAF PHILLIPS LAB. Aberdeen [142]	4.2-5	TE_{01}	4	0.5	1

Table XXI: First experimental results on gyro-BWOs (short pulse).

Institution	Frequency [GHz]	Mode	Power [kW]	Efficiency [%]	Pulse Length [ms]	
UNIV. TOHOKU, Sendai	10.0	$TE_{11}{}^{r}$	10	36	0.02	
[146-148]	10.5($2\Omega_c$)	$TE_{31}{}^{c}$	0.7	10		magnetron-
			1.3	7		type cavity
	10	$TE_{21}{}^{c}$	1.5	25		auto-res.

r: rectangular waveguide; c: circular waveguide

Table XXII: Experimental results of peniotrons.

Institution	Frequency [GHz]	Mode	Power [kW]	Efficiency [%]	Pulse Length [ms]
UNIV. TOHOKU, Sendai					
TOSHIBA, Nasushiobara	69.85($3\Omega_c$)	TE_{02}	8	6.75	0.2
UNIV. FUKUI [149]	140 ($3\Omega_c$)	TE_{03}	8	1	1

Table XXIII: Experimental results of gyropeniotrons.

11 Free electron masers (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, Le Barp [156]	33-36	0.3	80	TE_{11}^c	50	7.1(0.06)	43	1.75	0.4(50)	Pulse Line	0.01	amplifier
COLUMBIA U. NY [157,158]	24	0.05	34	TE_{11}^c/TM_{11}^c	2	3.3	20	0.6	0.1	Pulse Line	0.15	amplifier
	150	0.18	17	TE_{11}^c	5	4		0.8	0.15	Pulse Line	0.15	oscillator
DLR, Stuttgart [159]	100	0.1	20	TE_{02}^c	1	2		0.5	0.15	Pulse Line	0.1	superrad.
ENEA Frascati [160]	110-150	0.61	25	TE_{01}^r	0.0015	0.19		2.3	0.00035	Microtron	5.5	oscillator
EP Palaiseau [161]	120	0.03	20	TE_{11}^c	11.5	6.4		0.6	0.3	Electrostatic	0.02	superrad.
General Electric	2.6	0.04		TE_{01}^r	1.2	10		0.17	0.07	Electrostatic		oscillator
Microwave Lab, Palo Alto	2.8	0.04		TE_{01}^r	0.9	9.2	6	0.14	0.07	Electrostatic		amplifier
[153]	15.7			TE_{01}^r	1.65	6		0.23	0.125	Electrostatic		oscillator
	54			TE_{01}^r	0.15	6	30	0.07	0.04	Electrostatic		amplifier
IEE, China [155]	35	0.31	110		140	5.2	57	3.4	0.95	Ind. LINAC	0.05	amplifier
IAP, Nizhny Novgorod [162]	16.7	0.02		TE_{01}^c	300	11		0.6	4.5	Electrostatic	0.03	oscillator
	42.8-47.2	0.07	24	TE_{10}^r	7	12		0.5	0.12	Pulse Line	0.015	oscillator
IAP,N.N./INP Novosib.[163]	75	0.08	40	TE_{11}^c	50	2		1.0	2.4	Pulse Line	5	oscillator
JINR Dubna/IAP N.Novg.	31	0.27	60	TE_{11}^c	23	19		0.8	0.15	Ind. LINAC	0.2	oscillator
JINR Dubna [164]	35	0.19	72	TE_{11}^c	30	10		1.5	0.2	Ind. LINAC	0.2	amplifier
ILE Osaka [165]	250	0.05	30	TE_{11}^c	0.6	0.5	110	0.6	0.2	Ind. LINAC	0.04	amplifier
ILT/ILE Osaka [166]	110	0.71	60	TE_{01}^r	1	0.2		9.0	0.05	RF LINAC	4×10^{-6}	oscillator
ISAS, Sagamihara [167]	11.8	0.09	32.7	TM_{81}^c	3	1		0.43	0.19	Pulse Line	0.4	oscillator
JAERI, Ibaraki [168]	45	0.18	45	TE_{11}^c	6	2.9	52	0.82	0.25(2.0)	Ind. LINAC	0.03	amplifier
KAERI, Korea [155]	260	0.13	32		0.001	0.15		0.4	0.0017	Electrostatic	10-30	oscillator
KEK, Tsukuba [169,170]	9.4	0.121	160	TE_{01}^r	120	17.8(6.2)	21	1.5	0.45(1.3)	Ind. LINAC	0.015	superrad.
LLNL, Livermore [17,171]	34.6	0.37	98	TE_{01}^r	1000	34	52	3.5	0.85(4.0)	Ind. LINAC	0.02	amplifier
[172]	140	0.17	98	TE_{11}^c	2000	13.3	58	6.0	2.5 (3.0)	Ind. LINAC	0.02	amplifier
MIT, Cambridge [113,173]	9.3	0.02	33	TE_{11}^c	0.1	10	6	0.18	0.0055	Electrostatic	0.02	amplifier
	27.5	0.05	30	TE_{11}^c	1	10.3	-	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	26	0.31	0.03(0.05)	Electrostatic	1	amplifier
NRL, Washington D.C.	13.2-16.6	0.1	25.4	TE_{11}^c	4.2	18	29	0.245	0.094	Modulator	1.2	amplifier
[174,175]	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. [155]	95	0.2	100		10	4		2.5	0.1	Pulse Line	0.25	oscillator
RI, Moscow [176]	6-25	0.03	48	TE_{11}^c/TM_{01}^c	10	1.7		0.6	1	Pulse Line	2	superrad.
SIAE, Chengdu [177]	37	0.125	34.5	TE_{11}^c	7.6	5.4		0.5	0.28	Electrostatic	0.015	oscillator
SIOFM, Shanghai [178,179]	37.5	0.12	21	TE_{11}^c	12	3.7	50	0.4	0.8	Pulse Line	0.02	amplifier
	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	superrad.
TRW, Redondo Beach [180]	35	0.16	20	TE_{01}^r	0.1	9.2		0.3	0.004	Electrostatic	10	oscillator
	35	0.16	20	TE_{01}^r	0.1	9.2	2	0.29	0.004	Electrostatic	10	amplifier
UNIV. MARYLAND [155]	85	0.36	9.6		0.25	3.3		0.45	0.017	Pulse Line	0.02	amplifier
UCSB Santa Barbara [181]	120-880	0.15	71.4		0.027	0.5		2-6	0.002	Electrostatic	1-20	oscillator
UNIV. Tel Aviv [155]	4.5	0.03	44		0.0023	4		0.07	0.0008	Electrostatic	5	superrad.
UNIV. Twente [182]	35	0.19	30	TE_{11}^c/TM_{01}^c	2.3	0.6		0.5	0.75	Pulse Line	0.1	superrad.

r: rectangular waveguide; c: circular waveguide

Table XXIV: State-of-the-art of millimeter- and submillimeter wave FEMs.

mmw frequency	130-260 GHz	f_{mmw}
Rapid tuneability of f_{mmw}	+/- 5%	Δf_{mmw}
Tuning time over 10% of f_{mmw}	10 ms	Δt_{mmw}
mmw output power	1 MW	P_{mmw}
Electron energy	1.35-2 MeV	T_e
Electron beam current	12 A	I_e
Electron loss current	< 20 mA	I_{loss}
Normalized beam emittance	80 π mm mrad	ε_n
Pulse length	100 ms	t_p
Duty cycle	10^{-3}	
Overall efficiency (grid to P_{mmw})	60%	η_P
Linear gain	7	Γ_{lin}
Gain in saturation	3.5	Γ_{sat}
Waveguide mode	HE_{11}	
Type of waveguide	rectangular corrugated	
Cross section of primary waveguide	15*20 mm^2	a*b
Separation mmw beam, electron beam	via stepped waveguide	
Undulator period	40 mm	λ_u
Undulator gap	25 mm	g_u
Peak undulator field, section 1	0.2 T	B_{u1}
Number of full cells, section 1	20	N_{u1}
Peak undulator field, section 2	0.16 T	B_{u2}
Number of full cells, section 2	14	N_{u2}
Total number of cells (incl. matching)	38	N_u
Length of undulator	1.58 m	L_u

Table XXV: Design parameters of the planned FOM-FEM [154]

12 Comparison of gyrotron and FEM for nuclear fusion

Table XXVI lists a comparison of the main performance parameters and features of gyrotron oscillators and FEMs for ECRH of plasmas in nuclear fusion research. The important advantage of the FEM is its a and continuous frequency tunability and the possibility of high unit power but the gyromonotron is a much simpler device. Up to now, the cylindrical cavity gyrotron is the only millimeter wave source which has had an extensive on-the-field experience during fusion plasma heating experiments over a wide range of frequencies and power levels (8-159 GHz, 0.1-0.9 MW).

	Gyrotron Oscillator (cyclotron resonance maser axial magnetic field)	Free Electron Maser Oscillator (periodic transverse magnetic field)
1. Beam voltage	low (70 - 95kV)	high (0.2 - 2 MV)
2. Magnetic field (140 GHz)	high (5.5 T, 1st harmonic)	low (0.2 T, wiggler)
3. Frequencies	8 - 650 GHz	9 GHz - visible
4. Frequency tunability	$\Delta U_{beam} + \Delta U_{mod}$: fast step tuning (5 %) ΔB: slow step tuning (25 %)	ΔU_{beam}: fast continuous tuning (10%) slow mechanical tuning (50%)
5. Electron beam	magnetron injection gun	Pierce electron gun, acceleration and deceleration tubes, beam optics
6. Ohmic losses in cavity	cutoff cavity 2 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 (noise source?)
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	2-4 on ground potential 0.9 % ohmic losses	15-25 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 (140 GHz) present status	high average power 0.6 MW/3s (coax. 1.1 MW/200 μs)	2GW/20ns but very low duty cycle (LLNL amplifier)
14. Exp. system efficiency without energy recovery	high 40 %	low 5-10 %
15. Collector loading	relatively low	high
16. Theor. system efficiency with depressed collector	60 % (exp. 51 %)	60 % (but halo current ?)
17. Physical size	3 m x 3 m x 3 m	12 m x 3 m x 3 m
18. Power per unit (140 GHz)	1 MW (coax., 2.5 MW)	5 MW

Table XXVI: Comparison of parameters and features of gyrotron oscillators and FEMs for ECRH.

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