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State-of-the-Art of High Power Gyro-Devices and Free Electron Masers Update 1997

M. Thumm
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Forschungszentrum Karlsruhe GmbH
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STATE-OF-THE-ART OF HIGH POWER GYRO-DEVICES AND FREE ELECTRON MASERS UPDATE 1997

Abstract

Gyrotron oscillators (gyromonotrons) 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. 118 GHz (140 GHz, 170 GHz) gyrotrons with output power P_{out} = 0.53 MW (0.55 MW, 0.66 MW), pulse length τ = 5.0 s (3.0 s, 1.8 s) and efficiency η = 32 % (36 %, 32 %) 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 coaxial cavity gyrotrons, gyrotrons for technological applications, relativistic gyrotrons, quasi-optical gyrotrons, fast- and slow-wave cyclotron autoresonance masers (CARMs), gyroklystrons, gyro-TWT amplifiers, gyrotwystron amplifiers, gyro-BWO's, gyropeniotrons, free electron masers (FEMs) and of vacuum windows for such high-power mm-wave sources. The highest CW powers produced by gyrotron oscillators, gyroklystrons and FEMs are, respectively, 340 kW (28 GHz), 2.5 kW (92 GHz) and 36 W (15 GHz).

STATUS DER ENTWICKLUNG VON HOCHLEISTUNGS-GYRO-RÖHREN UND FREI-ELEKTRONEN-MASERN STAND: ENDE 1997

Übersicht

Gyrotronoszillatoren (Gyromonotrons) werden vorwiegend als Hochleistungsmillimeterwellenquellen für die Elektron-Zyklotron-Resonanzheizung (ECRH) und Diagnostik von magnetisch eingeschlossenen Plasmen zur Erforschung der Energiegewinnung durch kontrollierte Kernfusion eingesetzt. 118 GHz (140 GHz, 170 GHz) Gyrotrons mit einer Ausgangsleistung von P_{out} = 0.53 MW (0.55 MW, 0.66 MW) bei Pulslängen von τ = 5.0 s (3.0 s, 1.8 s) und Wirkungsgraden von η = 32% (36 %, 32 %) 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 mit koaxialem Resonator, Gyrotrons für technologische Anwendungen, relativistischen Gyrotrons, quasi-optischen Gyrotrons, Zyklotron-Autoresonanz-Masern (CARMs) mit schneller oder langsamer Welle, Gyroklystrons, Gyro-TWT-Verstärkern, Gyrotwystron-Verstärker, Gyro-Rückwärtswellenoszillatoren (BWOs), Gyro-Peniotrons, Frei-Elektronen-Maser (FEM) und von Vakuumfenstern für solche Hochleistungsmillimeterwellenquellen berichtet. Die höchsten von Gyrotronoszillatoren, Gyroklystrons und FEMs erzeugten CW-Leistungen sind 340 kW (28 38GHz), 2.5 kW (92 GHz) bzw. 36 W (15 GHz).

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 (28-160 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) [1-7] 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 100-960 kW at frequencies between 28 and 160 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 [8] and stellarators [9]. The confining magnetic fields in present day fusion devices are in the range of B_o=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 [10]. 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 with conventional cylindrical cavity, capable of high average power 0.5 - 1 MW per tube, CW, and 2 MW coaxial-cavity gyrotrons 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 [11]. Slow frequency tuning has been shown to be possible on quasi-optical Fabry-Perot cavity gyrotrons [12] as well as on cylindrical cavity gyrotrons with step tuning (different working modes) [13-15].

This work reports on the status and future prospects of the development of gyrotron oscillators for ECRH but also refers to the development of very high frequency gyromonotrons for active plasma diagnostics [16,152].

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 [17-19]. 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 company in Japan is employing a permanent magnet system [20]. 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 [21]. 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 [22,23]. Therefore this report gives an overview of the present development status of relativistic gyrotrons, fast- and slow-wave 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 achievements in the development of gyro-devices, free electron masers and of vacuum windows for such high-power mm-wave sources reviewed in [10] and in the FZKA Reports 5564 (April 1995), 5728 (March 1996) and 5877 (February 1997) 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 [24]

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

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 [24,25], 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 [1,26]: Richard Twiss in Australia [27], Jürgen Schneider in the US [28] and Andrei Gaponov in Russia [29]. 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 [1,26]. The predominance of the fast-wave ECM resonance with its azimuthal bunching in producing microwaves was experimentally verified in the mid-1960s in the US [30] (where the term "electron cyclotron maser" was apparently coined) and in Russia [31].

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 [32-34], 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 [1-5].

Gyrotron oscillators and gyroklystrons are devices which usually utilize only weakly relativistic electron beams (<100 kV) with high transverse momentum (pitch angle $\alpha = v_\perp/v_z > 1$) [35]. 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 [32-35]. 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 [1-7,32-35]. Modern high-power high-order volume mode gyrotron oscillators for fusion plasma applications employ an internal quasi-optical mode converter with lateral microwave output (Tables II-IX).

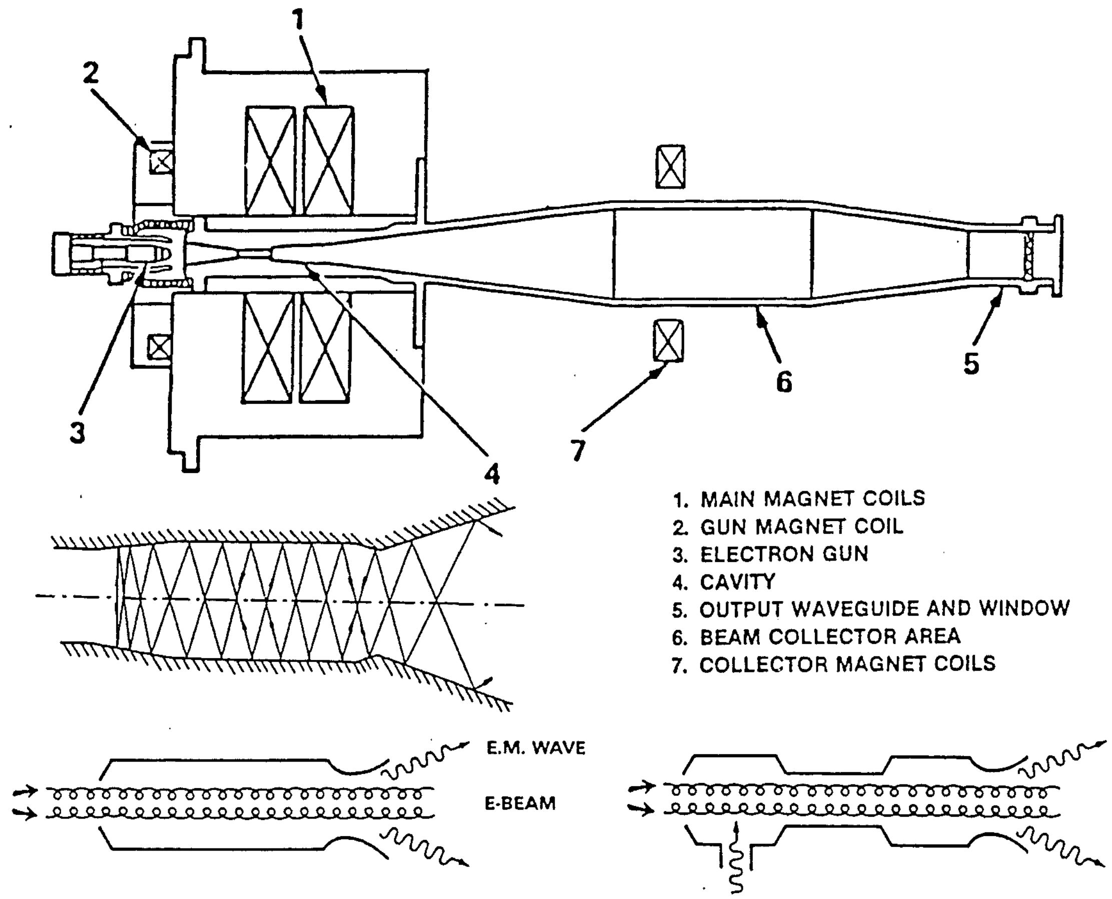


Fig. 1: Schematic of VARIAN CW gyrotron oscillator [6] and scheme of irregular waveguide cavities of gyromonotron oscillator (left) and gyroklystron amplifier [32].

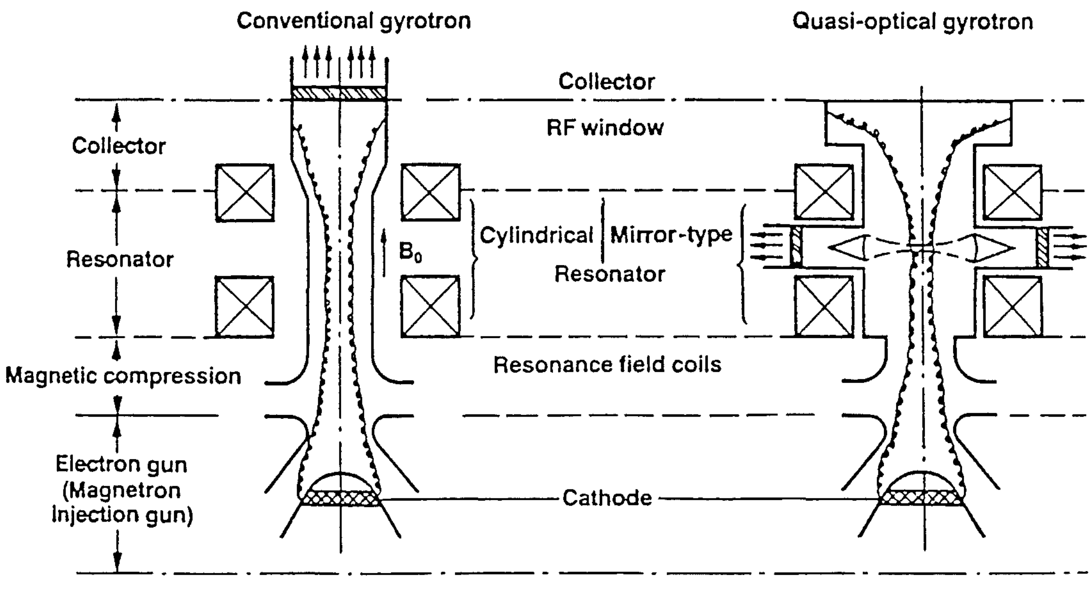


Fig. 2: Principle of a conventional gyrotron with cylindrical resonator and of a quasi-optical gyrotron with mirror resonator [12].

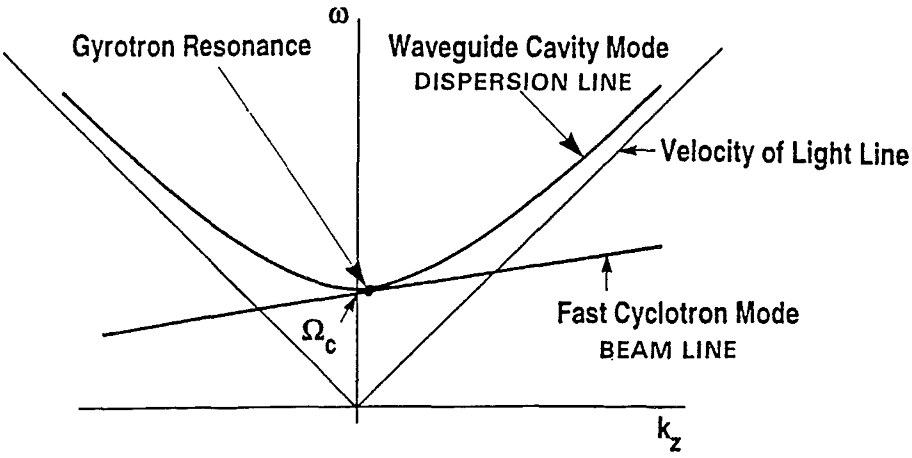


Fig. 3 Dispersion diagram of gyrotron oscillator (fundamental resonance)

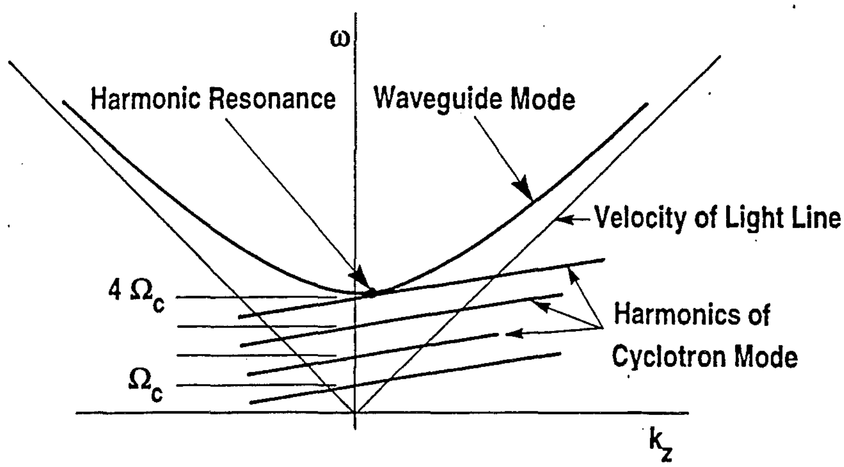


Fig. 4 Dispersion diagram of harmonic frequency gyrotron oscillator

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 [24]. Fig. 5 shows how

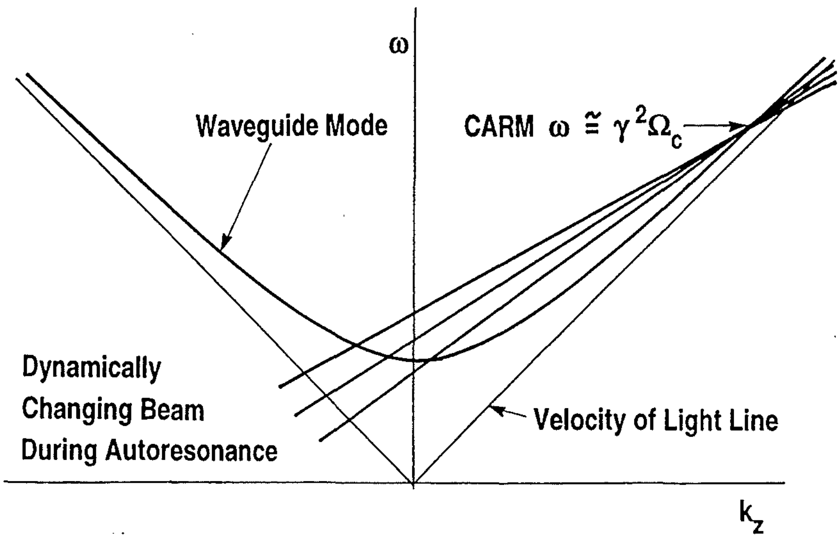


Fig. 5: Dispersion diagram of the cyclotron autoresonance maser (CARM).

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) [24] 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_o. 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.

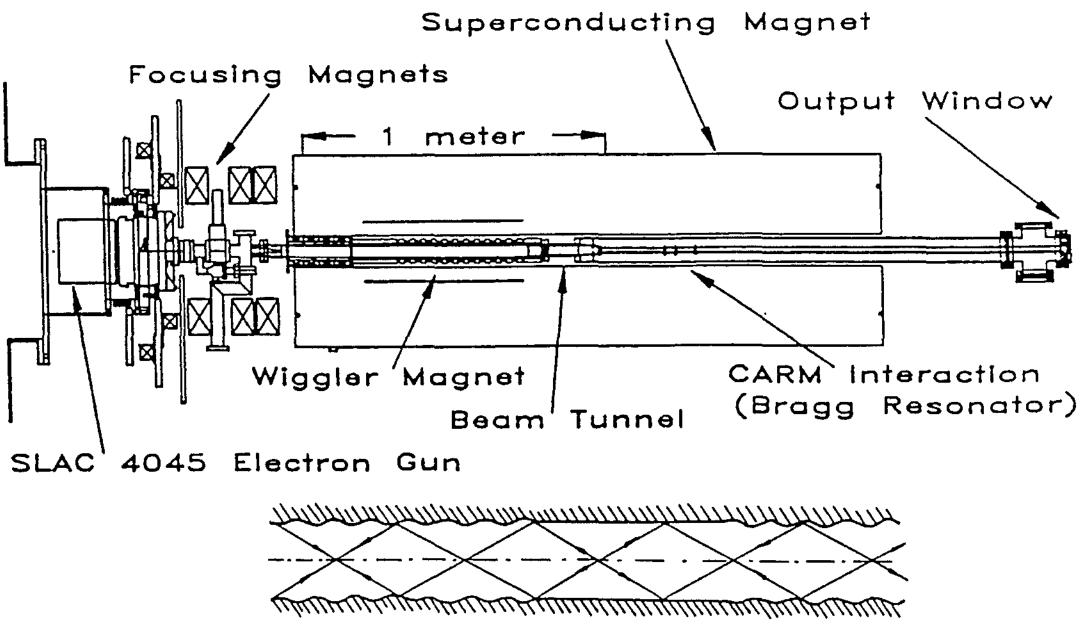


Fig. 6: Schematic of the long-pulse MIT CARM oscillator experiment [36] and scheme of a Bragg resonator [24].

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%. [24,35].

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 on the electron beam and the slow electromagnetic waves of the cavity 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 [37-40], 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 waves.

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 nearly matched and the group

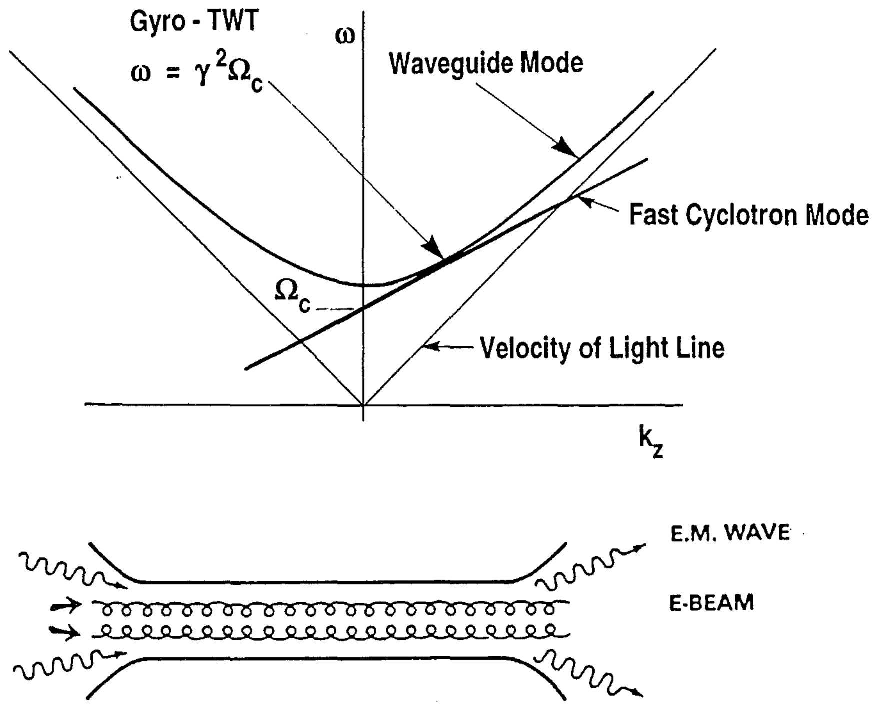


Fig. 7: Dispersion diagram and scheme of interaction circuit of Gyro-TWT amplifier.

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 [41].

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. The gyrotwystron configuration 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 an output cavity. The inverted gyrotwystron is a device consisting of the input waveguide, drift section, and output cavity [42]. The travelling 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 (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 frequency of

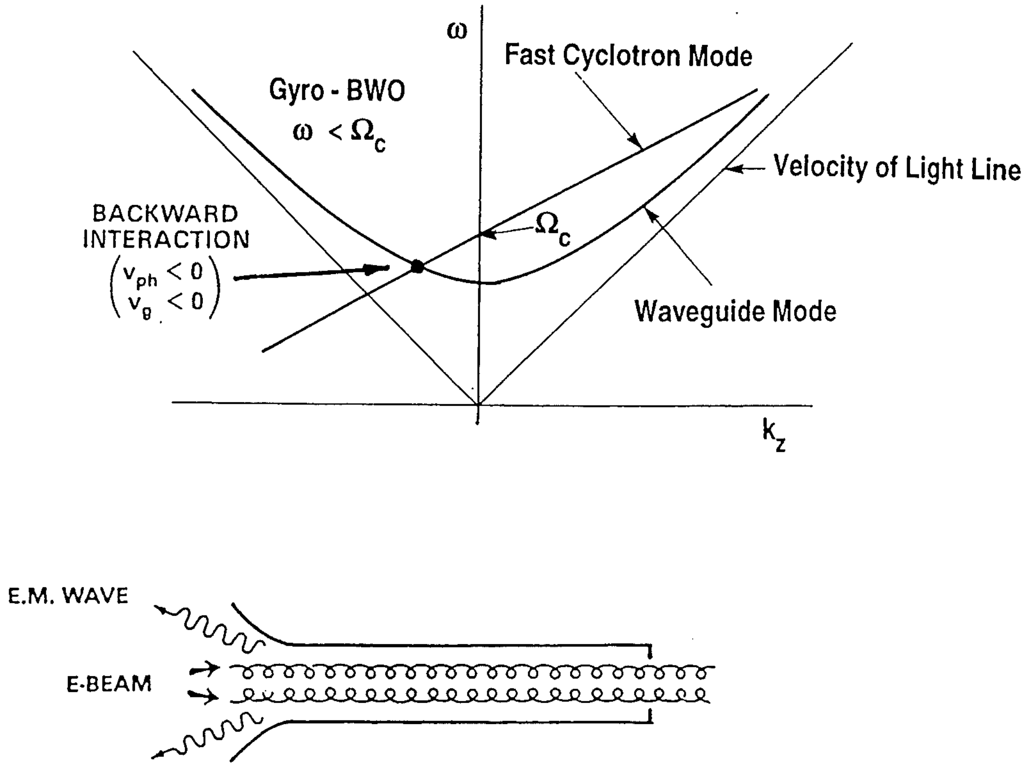


Fig. 8: Dispersion diagram and scheme of interaction circuit of Gyro-BWO.

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_o. 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 linear 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 linear-beam (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 simplified 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.

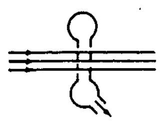
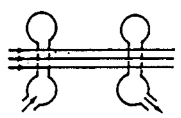
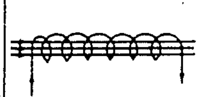
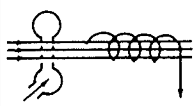
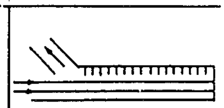
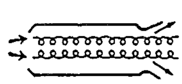
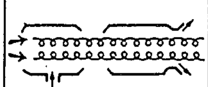
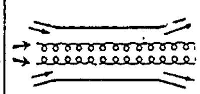
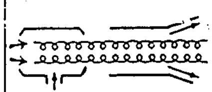
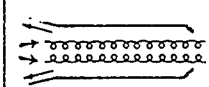
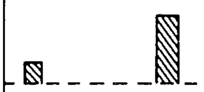
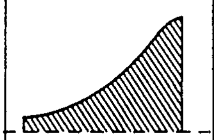
"0" TYPE DEVICE	 MONOTRON	 KLYSTRON	 TWT	 TWYSTRON	 BWO
TYPE OF GYROTRON	 GYRO-MONOTRON	 GYRO-KLYSTRON	 GYRO TWT	 GYRO-TWYSTRON	 GYRO BWO
RF FIELD STRUCTURE					
ORBITAL EFFICIENCY	0.42	0.34	0.7	0.6	0.2

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

In Tables XVI, XXIII and XXIV 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 [32-35].

4 Principle of Free Electron Lasers

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 [32,34,43-45]. 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. 9 and Section 2). In this respect, perhaps a more descriptive name is that coined by R.M. Phillips [46]: 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 are sometimes called scattrons [1,24]. 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.

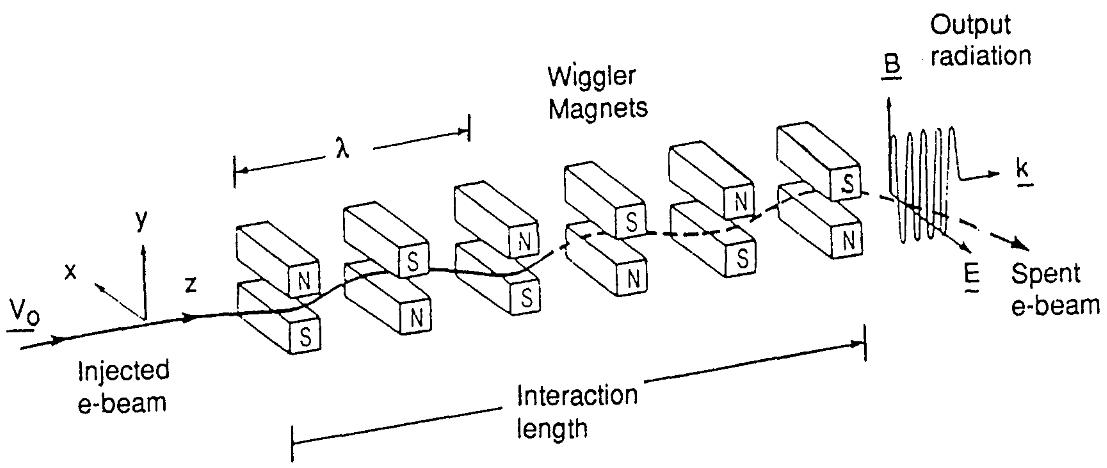


Fig. 9: The basis FEM configuration. Electrons in an injected electron beam undulate in the periodic magnetic field of the wiggler.

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 servere problems, and even higher frequencies are quite feasible. Rapid tunability over more than ± 5 % could be obtained by variation of the beam energy. The interaction occurs in a cavity 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) are compatible with a high unit power if the electron beam interception could be maintained at an acceptable level. A survey of FEM development status (experiments) is presented in Table XXIV.

5 Gyrotron Oscillators and Microwave Vacuum Windows for Plasma Heating

Institution	Frequency [GHz]	Mode cavity	Mode output	Power [MW]	Efficiency [%]	Pulse length [s]
ABB, Baden [47]	8	TE_{01}	TE_{01}	0.35	35	0.5
	39	TE_{02}	TE_{02}	0.25	42	0.1
HUGHES, Torrance [32]	60	TE_{02}	TE_{02}	0.2	35	0.1
IAP, Nizhny Novgorod [48]	25	$TE_{03}(2\Omega_c)$	TE_{03}	0.8	40 (twin-beam)	0.0001
IEAS, Beijing [49]	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
LAP/INPE, Sao Paulo [50]	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 [51]	88	$TE_{8,2}$	TEM_{00}	0.35	29	0.1
NEC, Kawasaki [52]	35	TE_{01}	TE_{01}	0.1	30	0.001
NRL, Washington D.C. [32,53]	35	TE_{01}	TE_{01}	0.15	31	0.02
	35	TE_{04}	TE_{04}	0.475	38	0.001
	35	TE_{24}	TE_{24}	0.43	40	0.001
PHILIPS 1), Hamburg [54]	70	TE_{02}	TE_{02}	0.14	30	CW
GYCOM-N (SALUT, IAP)	28	TE_{42}	TEM_{00}	0.5	40	0.1
Nizhny Novgorod	37.5	TE_{62}	TEM_{00}	0.5	35	0.2
[7,14,55,56]	53.2	TE_{83}	TEM_{00}	0.52	40	0.2
	75	TE_{94}	TEM_{00}	0.5	37	0.2
	82.7	$TE_{10,4}$	TEM_{00}	0.6	38	2.0
				0.67	59.7 (SDC)	2.0
				0.9	32	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 [57]	35	TE_{02}	TE_{02}	0.2	43	0.15
TOSHIBA, Otawara [58]	28	TE_{02}	TE_{02}	0.2	35.7	0.075
	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), Palo Alto [6,59,60]	8	TE_{21}	TE_{10}	0.5	33	1.0
	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, Toki [61,62]				0.4	28	10.5
				0.2	21	30
				0.1	14	CW
				0.64	32	0.001
				0.59	41 (SDC)	0.001

SDC: Single-stage Depressed Collector

1) formerly VALVO, 2) Communications & Power Industries, formerly 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 [15,64-67]	117.9	$TE_{19,5}$	TEM_{00}	1.0	25	0.001
				1.0	41(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 [68,69]	120	$TE_{15,2}$	$TE_{15,2}$	1.02	32.5	0.0002
				0.46	30	0.1
				0.25	30	0.21
GYCOM-N(SALUT, IAP)	106.4	$TE_{15,4}$	TEM_{00}	0.5	33	0.5
Nizhny Novgorod [7,14,55,56]	110	$TE_{15,4}$	TEM_{00}	0.5	33	0.5
GYCOM-M(TORIY, IAP)	110	$TE_{19,5}$	TEM_{00}	1.2	40	0.0001
Moscow, N.Novgorod				1.0	65(SDC)	0.0001
[7,56,70-72]				0.93	36	2.0
				0.5	35	5.0
				0.33	33	10.0
THOMSON, Velizy [57]	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	0.01
[74-76]				0.53	32	5.0
JAERI, TOSHIBA	110	$TE_{22,2}$	TEM_{00}	0.75	27.6	0.002
Naka, Otawara [77-81]				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 [6,60,82-85]	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}	1.09	32	0.6
				0.53	30	2.0
				0.4	28	6.5
				0.35	27	10.2
				0.106	21	CW

SDC: Single-stage Depressed Collector
1) formerly KfK, 2) Communications & Power Industries, formerly 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)], [86]	140.8	TE_{03}	TE_{03}	0.12	26	0.4
FZK, Karlsruhe	140.2	$TE_{10,4}$	$TE_{10,4}$	0.69	28	0.005
[15,64-67,86-92]	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}	1.35	30	0.001
				1.35	49(SDC)	0.001
				0.8	58(SDC)	0.001
	162.3	$TE_{25,7}$	TEM_{00}	1.1	28	0.001
				1.1	49(SDC)	0.001
GYCOM-N(SALUT, IAP)	140	$TE_{22,6}$	TEM_{00}	0.8	32	0.8
Nizhny Novgorod				0.89	50.5(SDC)	0.8
[7,14,55,56]				0.8	53.5(SDC)	1.0
				0.55	33	2.0
	158.5	$TE_{24,7}$	TEM_{00}	0.5	30	0.75
	170	$TE_{28,7}$	TEM_{00}	1.0	32.5	0.0001
	170	$TE_{25,10}$	TEM_{00}	1.4	35	0.0001
				1.0	62(SDC)	0.0001
GYCOM-M(TORIY, IAP)	140	$TE_{22,6}$	TEM_{00}	1.0	36	1.0
Moscow, N.Novgorod				0.96	36	1.2
[7,56,71-73,93-98]				0.735	36	1.5
				0.65	36	2.5
				0.55	36	3.0
				0.25	36	5.0
				0.14		9.3
	170	$TE_{25,10}$	TEM_{00}	1.0	32	0.1
				0.66	32	1.8
JAERI, TOSHIBA	170	$TE_{22,6}$	TEM_{00}	0.45	19	0.05
Naka, Otawara [99-102]				0.25	19	0.4
				0.25	32(SDC)	0.4
	170.1	$TE_{31,8}$	$TE_{31,8}$	1.15	29	0.0004
	170.2	$TE_{31,8}$	TEM_{00}	0.525	19	0.6
				0.525	32(SDC)	0.6
				0.23		2.2
	170	$TE_{31,8}$	TEM_{00}	0.75	22	0.0004
				0.75	40(SDC)	0.0004
				0.52	36(SDC)	0.75
				0.21	32(SDC)	4.0
				0.175	30(SDC)	10.0
NIFS, TOSHIBA	168	$TE_{31,8}$	TEM_{00}	0.5	19	0.1
Toki, Otawara [62]				0.35	19	0.3
CPI[3)],	140	$TE_{02/03}$	TE_{03}	0.1	27	CW
Palo Alto [6,60]	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)] formerly KfK, [2)] formerly VALVO, [3)] Communications & Power Industries, formerly 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[105-112]	137.78	$TE_{27,16}$	$TE_{27,16}$	1.03	24.3	yes	no
Pulse Length 0.5 ms	139.96	$TE_{28,16}$	$TE_{28,16}$	1.17	27.2	yes	no*
			TEM_{00}	0.95	20	yes	no
				0.95	29(SDC)	yes	no
				(dual-beam output, 7 ms)			
	142.02	$TE_{29,16}$	$TE_{29,16}$	1.04	24.4	yes	no
	158.93	$TE_{32,18}$	$TE_{32,18}$	1.16	26.2	yes	no
	164.98	$TE_{31,17}$	$TE_{31,17}$	1.17	26.7	yes	no
	167.14	$TE_{32,17}$	$TE_{32,17}$	1.02	26.8	yes	no
IAP, Nizhny Novgorod	45	$TE_{15,1}$	$TE_{15,1}$	1.25	43	no	no
[5,7,35,113,114]	100	$TE_{21,18}$	$TE_{21,18}$	1.0	35	yes	no
Pulse Length 0.1 ms				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
	140	$TE_{28,16}$	$TE_{28,16}$	1.5	33	yes	no*
			$TE_{76,2}$	1.27	35.2	yes	yes
			TEM_{00}	1.08	30	yes	yes
				(dual-beam output)			
	224($2\Omega_c$)	$TE_{33,8}$	$TE_{33,8}$	0.1	11	yes	no
IAP, FZK[1)] Karlsruhe [105]	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 [115,116]	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

[1)] formerly KfK, * very similar cavity and tube design

Coaxial Cavity Gyrotrons

Table IV: Present experimental development status of short pulse (3 μs - 7 ms) coaxial cavity gyrotron oscillators.

Institution	Frequency [GHz]	Mode cavity	Mode output	Power [MW]	Efficiency [%]	Pulse length [s]
CPI[1], NIFS	84	$TE_{15,3}$	TEM_{00}	0.64	32	0.001
Palo Alto, Toki [62]				0.59	41(SDC)	0.001
FZK[2], Karlsruhe	117.9	$TE_{19,5}$	TEM_{00}	1.0	25	0.001
[15,64-67,86-92]				1.0	41(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
				1.35	30	0.001
				1.35	49(SDC)	0.001
				0.8	58(SDC)	0.001
	154.8	$TE_{12,4}$	TEM_{00}	0.35	18	0.01
				0.35	27(SDC)	0.005
	162.3	$TE_{25,7}$	TEM_{00}	1.1	28	0.001
				1.1	49(SDC)	0.001
GYCOM-N (SALUT, IAP)	82.7	$TE_{10,4}$	TEM_{00}	0.6	38	2.0
Nizhny Novgorod [72,98]				0.67	59.7(SDC)	2.0
	110	$TE_{19,5}$	TEM_{00}	1.2	40	0.0001
				1.0	65(SDC)	0.0001
	140	$TE_{22,6}$	TEM_{00}	0.8	32	0.8
				0.89	50.5 (SDC)	0.8
				0.8	53.5 (SDC)	1.0
	170	$TE_{25,10}$	TEM_{00}	1.4	35	0.0001
				1.0	62(SDC)	0.0001
NRL, Washington D.C. [123]	115	QOG	TEM_{00}	0.60	9	10^{-5}
				0.43	12.7(SDC)	10^{-5}
				0.20	16.1(SDC)	10^{-5}
JAERI, TOSHIBA	110	$TE_{22,2}$	TEM_{00}	0.75	27.6	0.002
Naka, Otawara[78-81,99-102]				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
	170.2	$TE_{31,8}$	TEM_{00}	0.75	22	0.0004
				0.75	40(SDC)	0.0004
				0.52	36(SDC)	0.75
				0.21	32(SDC)	4.0
				0.175	30(SDC)	10.0

SDC: Single-stage Depressed Collector; QOG: Quasi-Optical Gyrotron
[1]Communications & Power Industries, formerly VARIAN, [2] formerly KfK

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

Institution	Frequency [GHz]	Mode cavity	Mode output	Power [MW]	Efficiency [%]	Pulse length [s]
FZK, Karlsruhe [15]	114.2	$TE_{18,5}$	TEM_{00}	0.85	22	0.001
	117.9	$TE_{19,5}$	TEM_{00}	1.0	26	0.001
				1.0	41 (SDC)	0.001
	121.6	$TE_{20,5}$	TEM_{00}	1.0	26	0.001
	125.3	$TE_{21,5}$	TEM_{00}	1.0	26	0.001
	128.9	$TE_{22,5}$	TEM_{00}	0.9	23	0.001
	132.6	$TE_{20,6}$	TEM_{00}	0.85	22	0.001
	136.2	$TE_{21,6}$	TEM_{00}	0.9	23	0.001
	140.1	$TE_{22,6}$	TEM_{00}	1.0	26	0.001
				1.0	43(SDC)	0.001
	143.7	$TE_{23,6}$	TEM_{00}	1.0	26	0.001
	147.4	$TE_{24,6}$	TEM_{00}	1.1	29	0.001
	151.2	$TE_{25,6}$	TEM_{00}	1.05	27	0.001
	154.9	$TE_{23,7}$	TEM_{00}	0.95	25	0.001
	158.5	$TE_{24,7}$	TEM_{00}	1.1	29	0.001
	162.3	$TE_{25,7}$	TEM_{00}	1.0	26	0.001
				1.0	46(SDC)	0.001
	166.0	$TE_{26,7}$	TEM_{00}	1.0	25	0.001

SDC: Single-stage Depressed Collector
1) formerly KfK

Table VI: Step-tunable conventional cavity 1 MW gyrotron with broadband Brewster window at FZK (U_c = 83 kV, I_b= 47 A).

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	930 330 550 660	110 110 140 170	2.0 10.0 3.0 1.8	GYCOM-M GYCOM-M GYCOM-M GYCOM-M
silicon nitride	single disk water edge + gas face cooled	130	84	30.0	NIFS/CPI
sapphire	single disk LN_2 edge cooled	530 285* 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	410 500	110 110	1.0 0.5	JAERI/TOSHIBA JAERI/GA
sapphire	double disk FC75 face cooled	200 400 350 350 200 500	60 84 110 110 140 170	CW 10.5 10.0 5.0 CW 0.6	CPI NIFS/CPI CPI JAERI/TOSHIBA CPI JAERI/TOSHIBA
sapphire	distributed water cooled	65** 200*	110 110	0.3 0.7	GA/JAERI GA/CPI
diamond	single-disk water edge cooled	300** 50 450 500 110	110 110 110 170 170	1.0 CW 2.0 2.0 10.0	CPI/FOM CPI/FOM GYCOM-M/GA JAERI/FZK JAERI/FZK

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

Tab. VII: Experimental parameters of high-power millimeter-wave vacuum windows [7,10,75,76,124-140].

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 [10,141]. The features of boron nitride, silicon nitride (Kyocera SN-287), sapphire, Au-doped silicon and CVD diamond at room temperature and of sapphire, Au-doped silicon and CVD diamond at cryo-temperatures are summarized in Tables VIIIa and VIIIb, where

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

and

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

The LN_2-edge-cooled sapphire window of the 118 GHz TTE gyrotron (0.5 MW, 210 s), that operates close to the allowable lower limits of these two parameters, has R' =130 and P_T=80.

Material	BN (CVD) p.c.	Si_3N_4 composite (SN-B)	Sapphire (Al_2O_3) s.c.	Silicon Au-doped s.c.	Diamond (PACVD) p.c.
Thermal Conductivity k [W/mK]	50	59	40	150	2000
Ultimate Bending Strength σ_B[MPa]	80	800	410	3000	600
Poissons Number ν	0.25	0.28	0.22	0.1	0.1
Density ρ [g/cm^3]	2.3	3.4	4.0	2.3	3.5
Specific Heat Capacity c_p [J/g K]	0.8	0.6	0.8	0.7	0.5
Young's Modulus E [GPa]	70	320	385	190	1050
Therm. Expans. Coeff. α [10^{-6}/K]	3	2.4	5.5	2.5	1.2
Permittivity (145 GHz) ε_r'	4.7	7.84	9.4	11.7	5.67
Loss Tangent (145 GHz) $\tan\delta$ [10^{-5}]	115	30	20	0.35	1
Metallizing/Brazing Bakeout	o.k.	o.k. 550°C	o.k. 550°C	o.k 550°C	o.k. 500°C vacuum
Possible Size ∅ [mm]	145	400	270	127	160
Cost	medium	high	high	low	very high
Failure Resistance R' $R' = k\sigma_B (1-\nu)/E\alpha$	14.2	44.5	6.0	852	858
RF-Power Capacity P_T $P_T = R'\rho\, c_P/((1+\varepsilon_r')\tan\delta)$	0.04	0.36	0.09	318	225
Radiation Sensitivity n(10^{20}-10^{21}n/m^2) γ/X (0.75 Gy/s)			no no	no no	no no

Tab. VIIIa: 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) [141].

Material	Sapphire (Al_2O_3) s.c.	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	3000	600
Poissons Number ν	0.22	0.1	0.1
Density ρ [g/cm^3]	4.0	2.3	3.5
Specific Heat Capacity c_p [J/g K]	0.8	0.7	0.5
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	5.63
Loss Tangent (145 GHz) tanδ [10^{-5}]	0.57 (0.2)	0.35	1
Metallizing/Brazing Bakeout	o.k. 550°C	o.k 550°C	o.k. 500°C vacuum
Possible Size ∅ [mm]	270	127	160
Cost	high	low	very high
Failure Resistance R' $R' = k\sigma_B (1-\nu)/E\alpha$	130 (2871)	7389	4286
RF-Power Capacity P_T $P_T = R'\rho\, c_P/((1+\varepsilon_r')\tan\delta)$	71 (4460)	2719	1132
Radiation Sensitivity n(0.3 · 10^{21}n/m^2) γ/X (0.75 Gy/s)	no no	no	no

Tab. VIIIb: 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) [141].

The comparison of R' and P_T for the three materials BN, Si_3N_4 and sapphire clearly shows that there is no chance to use these dielectrics as an edge-cooled, single-disk window at room temperatures. Experiments at CPI in the US and at NIFS and JAERI in JA confirmed, that even a double disk FC75-face-cooled sapphire window has a CW-power limit around 0.3-0.4 MW.

Using the available material parameters and employing various beam profiles, finite element computations revealed the options for 170 GHz, 1 MW, CW operation given in Table IX [10,141]. Options 1 to 3 being water cooled, are preferred for their simplicity, in particular for use a torus window.

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

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

Table IX: Options for 1 MW, CW, 170 GHz gyrotron windows. [10,141]

6 Very High Frequency Gyrotron Oscillators

Institution	Frequency [GHz]	Mode	Power [kW]	Efficiency [%]	Pulse length [ms]
CPI[1], Palo Alto [144]	250	$TE_{11,1}/TE_{11,2}$	10	3.4	0.1
IAP, N.Novgorod [16,145]	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 [146,147]	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 [148-152]	383	TE_{26}	3	3.7	1
	402	TE_{55}	2	3	1
	576	TE_{26}	1	2.5	0.5

[1] Communications & Power Industries, formerly VARIAN

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	113.2	$TE_{23,6}$	0.84	25	3
[13,116,146,147]	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	$TE_{27,8}$	1.50	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
IAP,	250	$TE_{20,2}$	0.3	31	30 - 80
Nizhny Novgorod [16]	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 [149]	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.

Operating at the fundamental or the 2nd harmonic of the electron frequency enables the gyrotron to act as a medium power (several 100 W) step tunable, mm- and sub-mm wave source in the frequency range from 150 to 847 GHz [148-154].

Institution	Frequency [GHz]	Mode	Voltage [kV]	Current [A]	Power [MW]	Efficiency [%]
MIT, Cambridge [103]	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 [72]) 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 [103]	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 [72]) operating at the fundamental electron cyclotron resonance (pulse length 1.5 μs).

7 Gyrotrons for Technological Applications

Institution	Frequency [GHz]	Mode cavity	Mode output	Power [kW]	Efficiency [%]	Voltage [kV]	Magnet
GYCOM-N(SALUT,IAP)	15	TE_{01}	TE_{01}	4	50	15	roomtemp.
Nizhny Novgorod,	30 ($2\Omega_c$)	TE_{02}	TE_{02}	10	25	20	roomtemp.
GYCOM-M(TORIY,IAP)	31.8-34.8	TE_{11}	TE_{11}	1.2	40	12	mech.tun.
Moscow, N.Novgorod	35.5-37.5	TE_{01}	TE_{01}	0.5	15.3	16	mech.tun.
[7,14,17-19,56,93,94,156-158]	35.15	TE_{02}	TE_{02}	9.7	43	25	cryo.mag.
	35	TE_{02}	TEM_{00}	10-40	30-40	25-30	cryo.mag.
	37.5	TE_{62}	TEM_{00}	20	35	30	cryo.mag.
	83	TE_{93}	TEM_{00}	10-40	30-40	25-30	cryo.mag.
	150	TE_{03}	TE_{03}	22	30	40	cryo.mag.
	160 ($2\Omega_c$)	TE_{03}	TE_{03}	2.4	9.5	18	cryo.mag.
MITSUBISHI, Amagasaki [20,160-162]	28 ($2\Omega_c$)	TE_{02}	TE_{02}	10	38.7	21	perm.mag. tapered B
CPI[1)], Palo Alto [6,144]	28	TE_{02}	TE_{02}	10	30.3	30	roomtemp.
	28 ($2\Omega_c$)	TE_{02}	TE_{02}	10.8	33.6	30	roomtemp.
CPI, NIFS Palo Alto, Toki [61,62]	84	$TE_{15,3}$	TEM_{00}	50	14	80	cryo.mag.

[1)] Communications & Power Industries, formerly VARIAN

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

8 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	
[163,164]	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 [164-167]	10	TE_{13}	0.3	1.0	60	15	plasma-filled, slotted cavity
	40	TE_{13}	0.4	1.3	25	5	slotted cavity
UNIV. Michigan [168,169]	3	$TE_{01}{}^{r}$	20	2(7)	0.8	1.3(0.4)	small orbit
			14	0.35(1.2)	0.8	5(0.15)	large orbit
	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
[170-172]	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. [173]	3.1		0.75	8.0(30)	1800	8	also viractor interaction
UNIV. Strathclyde [174]	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

Table XV: Present development status of relativistic gyrotron oscillators.

Institution	Frequency [GHz]	Mode	Harmonic No. s	Voltage [MV]	Current [kA]	Power [kW]	Efficiency [%]
IAP, Nizhny Novgorod	21.4	TE_{11}	1	0.3	0.03	100	1.1
[175,176]	35.7	TE_{21}	2	0.3	0.03	100	1.1
	49.1	TE_{31}	3	0.3	0.03	300	3.3
	62.4	TE_{41}	4	0.3	0.03	100	1.1
	74.9	TE_{51}	5	0.3	0.03	150	1.7

Table XVI: Relativistic large orbit harmonic pulse gyrotrons (τ = 10 ns).

9 Quasi-Optical Gyrotrons

Institution	Frequency [GHz]	Mode resonator	Power [kW]	Efficiency [%]	Pulse length [ms]	
ABB, Baden [47]	92	TEM_{00q}	90	10	10	
CRPP, Lausanne [12,177]	90.8	TEM_{00q}	150	15	5	
	100	TEM_{00q}	90	11	15	
	200(2Ω_c)	TEM_{00q}	8	3.5	15	
IAP, Nizhny Novgorod [178]	100	TE_{061}	260	6.5	0.04	echelette cavity
MIT, Cambridge [179]	136	TE_{061}	61.3	23	0.003	confocal slot-cavity
NRL, Washington D.C.	110	TEM_{00q}	80	8	0.013	
[123,180]	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	
Moscow-State Univ.	35	TEM_{00q}	1	15	CW	
[181]	95	TEM_{00q}	1	15	CW	
TOSHIBA, [58]	112	TEM_{00q}	100	12	5	
Otawara	120	TEM_{00q}	26	10 (DEB)	3	

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

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

10 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}	30	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	26(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 [175,176,182-185]	125	TE_{41}	10	2	-	0.9	0.5	1.0	oscil.
LLNL Livermore [186]	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.
[36,187,188]	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}	12	6.3(0.04)	30	0.7	1.5	0.13(20)	ampl.
UNIV. Michigan [189]	15	TE_{11}	7	1.5	-	0.45	0.4	1.2	oscil.
UNIV. Strathclyde [190]	14.3($2\Omega_c$)	TE_{21}	0.18	4(0.4)	-	0.2	0.3	0.015(0.15)	oscil.

IAP Nizhny Novgorod, IHCE Tomsk, JINR Dubna

Table XVIIIa: 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
UNV. Lomonosov, Moscow [37]	9.5	TM_{01}	35	3.5	-	1.15	0.4	2.5	oscil. corr.w.g.
Tomsk Polytechn. Inst. [38]	25		20	0.2	-	0.64	0.9	14	oscil. diel.w.g.
UNIV. Niigata, NIFS, UNIV. Maryland [39]	19.5	TM_{01}	0.2	3.8	-	0.9	0.035	0.15	oscil. corr.w.g.
UNIV. Yale, NRL, Washington D.C. [40]	6.2	TE_{01}	0.02	10	53	0.2	0.05	0.005	ampl. diel.w.g.

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

11 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	54	30	30	0.4	
[32,123,191-194]	35.0	TE_{01}	2	210	37	24		
	85	TE_{13}	2	50		20		
	85.5	TEM_{00}	2	82	19	18		QOGK
				82	30 (SDC)	18		QOGK
	93.4	TE_{01}	4	67	28	29	0.5	
IAP Nizhny Novgorod	9.25	TE_{01}	2	4	50	22	1.0	
[195-202]			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
	35.12 ($2\Omega_c$)	TE_{02}	2	258	18	17	0.3	tapered B-field
	35	TE_{02}	2	300	22		0.3	2-cav. gyrptron
				230	30		0.3	2-cav. gyrotron
GYCOM-M (TORIY),	35.2	TE_{02}	2	750	24	20	0.6	max. power
Moscow [197,198]			2	350	32	19	0.9	max. efficiency
	35.0	TE_{01}	4	160	48	42	1.4	
			3	250	35	40	1.4	
IAP Nizhny Novgorod	93.2	TE_{01}	4	65	26	35	0.3	max. power
[203]			4	57	34	40	0.3	max. efficiency
CPI[1], Palo Alto [32]	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	

QOGK: Quasi-Optical Gyroklystron; SDC: Single-stage Depressed Collector

[1] Communications & Power Industries, formerly VARIAN

Weakly Relativistic CW Gyroklystrons

Institution	Frequency [GHz]	Mode	No. of cavities	Power [kW]	Efficiency [%]	Gain [dB]	BW [%]
IAP Nizhny Novgorod	9.17	TE_{11}	2	0.7	70	22	0.3
IAP/ISTOK Moscow [199,200,203]	91.6	TE_{01}	4	2.5	25	31	0.36

Table XIXa: 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	30	33	0.25	
[202-209]	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
	19.75 ($2\Omega_c$)	TE_{02}	2	32	29	27	0.15	
	29.57 ($3\Omega_c$)	TE_{03}	2	1.8	2.0	14	0.1	

Table XIXb: Relativistic pulse gyroklystron experimental results.

Weakly Relativistic Pulse Gyro-TWTs

Institution	Frequency [GHz]	Mode	Power [kW]	Efficiency [%]	Gain [dB]	Bandwidth [%]	Type
UC LOS ANGELES	9.3	TE_{10}	55	11	27	11	diel.coat.waveg.
[210-214]	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	
[215,216]	35.8	TE_{11}	27	16	35	7	2-stage severed
	34.2	TE_{11}	62	21	33	12	2-stage lossy (short)
	33.8	TE_{11}	65	22	50	9	2-stage lossy (long)
NRL, Washington D.C.	32.5	TE_{10}	6.3	10	16.7	33	1-stage tapered
[32,217-219]	35.5	TE_{10}	8	16	25	20	2-stage tapered
	32.3	TE_{10}	50	28	25	11	folded waveguide axis-encircl.beam
	34.3	TE_{01}	16.6	7.8	20	1.4	
CPI[1], Palo Alto	5.18	TE_{11}	120	26	20	7.3	MIG
[32,220,221]	5.2	TE_{11}	64	14	17.5	7.3	Pierce-helix gun
	35	TE_{11}	50				Pierce-helix gun
	93.7	TE_{11}	28	7.8	16	3	Pierce-helix gun

[1] Communications & Power Industries, formerly VARIAN

Relativistic Pulse Gyro-TWTs

Institution	Frequency [GHz]	Mode	Power [MW]	Efficiency [%]	Gain [dB]	Bandwidth [%]	
MIT, Cambridge [222]	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. [223]	35	TE_{11}	20	11	30		explos.-emission gun, bifilar helical wiggler

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

Weakly Relativistic Pulse Gyrotwystrons

Institution	Frequency [GHz]	Mode cavity	Mode output w.g.	Power [kW]	Efficiency [%]	Gain [dB]	BW [%]
NRL, Washington, D.C.	4.5	TE_{10}	TE_{10}	73	22.5	37	1.5
[224]	31.5	TE_{42} $(2\Omega_c)$	TE_{42}	160	25	30	1.3
IAP, NRL, N. Novgorod	9.2	TE_{01}(2 cav.)	TE_{01}	4.8	30	20	0.9
Washington D.C. [225]				3.1	20	18	1.6

Weakly Relativistic Pulse Inverted Gyrotwystron

Institution	Frequency [GHz]	Mode input w.g.	Mode cavity	Power [kW]	Efficiency [%]	Gain [dB]	BW [%]
NRL, Washington, D.C.	31.8	TE_{22}	$TE_{42}(2\Omega_c)$	100	19	33	1.3
[42]	31.5	TE_{22}	$TE_{42}(2\Omega_c)$	160	25	30	0.3

Relativistic Pulse Gyrotwystrons

Institution	Frequency [GHz]	Mode cavity	Mode output w.g.	Power [MW]	Efficiency [%]	Gain [dB]	BW [%]
UNIV. MARYLAND	9.87	TE_{01}	TE_{01}	21.6	21	25.5	
[226]	19.76	TE_{01}(9.88 GHz)	$TE_{02}(2\Omega_c)$	12	11	21	

Table XXI: 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.	[227]	27.8	TE_{10}^{r}	2	9	3	electr. tuning
		29.2	TE_{10}^{r}	6	15	13	magn. tuning
UNIV. HSINCHU	[228]	34	TE_{11}^{c}	20-67	6.5-21.7	5	
				113	19	1	
MIT, Cambr., LLNL, Liverm.	[229]	140	TE_{12}^{c}	2	2	9	

r: rectangular waveguide; c: circular waveguide

Relativistic Pulse Gyro-BWOs (pulse duration = 0.1 - 1 μs)

Institution	Frequency [GHz]	Mode	Power [MW]	Efficiency [%]	BW [%]	Voltage [MV]	Current [kA]
UNIV. MICHIGAN	4-6	TE_{11}	55 (30)	8 (4.3)	1	0.7	1
[230,231]	5-6$(2\Omega_c)$	TE_{11}	1	0.15	4		
USAF PHILLIPS LAB.	4.2	TE_{21}	4	1	1	0.4	1
Aberdeen [232,233]	4.4	TE_{01}	0.15	0.04	1	0.4	1

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

Institution	Frequency [GHz]	Mode	Output Mode	Power [kW]	Efficiency [%]	Pulse Length [ms]	
UNIV. TOHOKU, Sendai	10.0	TE_{11}^{r}	TE_{11}^{r}	10	36	0.02	
[237-240]	10.5($2\Omega_c$)	TE_{31}^{c}	TE_{31}^{c}	0.7	10		magnetron-
				1.3	7		type cavity
	30.3($3\Omega_c$)	TE_{41}^{c}	TE_{01}^{c}	6.9	0.35		
	100 ($10\Omega_c$)	$TE_{11,1}^{c}$	TE_{01}^{c}	0.32	0.18		
	10	TE_{21}^{c}	TE_{21}^{c}	1.5	25		auto-res.

r: rectangular waveguide; c: circular waveguide

Table XXIII: 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 [241]	140 ($3\Omega_c$)	TE_{03}	8	1	1

Table XXIV: Experimental results of gyropeniotrons.

12 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,LeBarp[244]	33-36	0.3	80	TE_{11}^c	50	7.1(0.06)	43	1.75	0.4(50)	Pulse Line	0.01	amplifier
[245]	35	0.11	120	TE_{11}^c	80	4.5	39	2.2	0.8	Ind. LINAC	0.03	amplifier
COLUMBIA U. NY[246]	24	0.05	34	TE_{11}^c/TM_{11}^c	2	3.3	20	0.6	0.1	Pulse Line	0.15	amplifier
	150	0.185	17	TE_{11}^c	5	4		0.8	0.15	Pulse Line	0.15	oscillator
DLR, Stuttgart [247]	100	0.1	20	TE_{02}^c	1	2		0.5	0.15	Pulse Line	0.03	spon.emiss.
ENEA Frascati [248]	85-150	0.61	25	TE_{01}^r	0.0015	0.19		2.3	0.00035	Microtron	5.5	oscillator
EP Palaiseau [249]	120	0.03	20	TE_{11}^c	11.5	6.4		0.6	0.3	Electrostatic	0.02	superrad.
FOM Nieuwegein[242]	200	0.2/0.16	40	HE_{11}^r	0.29	2.7		1.76	0.0061	Electrostatic	3.0	oscillator
General Electric	2.6	0.04		TE_{01}^r	1.2	10		0.17	0.07	Modulator		oscillator
Microwave Lab, Palo Alto	2.8	0.04		TE_{01}^r	0.9	9.2	6	0.14	0.07	Modulator		amplifier
[46]	15.7			TE_{01}^r	1.65	6		0.23	0.125	Modulator		oscillator
	54			TE_{01}^r	0.15	6	30	0.07	0.04	Modulator		amplifier
IEE, China [243]	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
[250-252]	42.8-47.2	0.03	24	TE_{10}^r	7	12(0.5)		0.5	0.12(3)	Pulse Line	0.015	oscill./CRM
IAP,N.N./INP Novosib.[253]	75	0.08	40	TE_{11}^c	100	4		1.0	2.4	Pulse Line	2	oscillator
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
[254,255]	31.0	0.10	60	TM_{11}^c	39	24(19)		0.8	0.2(0.25)	Ind. LINAC	0.2	oscillator
	38.2	0.06	60	TM_{12}^c	3	3(2)		0.8	0.15(0.2)	Ind. LINAC	0.2	oscillator
	35	0.19	72	TE_{11}^c	30	10		1.5	0.2	Ind. LINAC	0.2	amplifier
ILE Osaka [256]	250	0.05	30	TE_{11}^c	0.6	0.5	110	0.6	0.2	Ind. LINAC	0.04	amplifier
ILT/ILE Osaka [257]	60-110	0.71	60	TE_{01}^r	0.01	0.2		9.0	0.05	RF LINAC	4×10^{-6}	oscillator
ISAS, Sagamihara [258]	11.8	0.09	32.7	TM_{81}^c	3	1		0.43	0.19	Pulse Line	0.4	oscillator
JAERI, Ibaraki [259-260]	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 [261]	27	0.13	32	TM_{11}^c	0.001	0.15		0.4	0.0017	Electrostatic	10-30	oscillator
KEK, Tsukuba [262-264]	9.4	0.121	160	$TE_{\varnothing 1}^r$	100	12.1(5.1)	21	1.5	0.55(1.3)	Ind. LINAC	0.015	amplifier
LLNL, Livermore [25,265]	34.6	0.37	98	TE_{01}^r	1000	34(7.2)	52	3.5	0.85(4.0)	Ind. LINAC	0.02	amplifier
[25,265,266]	140	0.17	98	TE_{11}^c	2000	13.3(10)	58	6.0	2.5 (3.0)	Ind. LINAC	0.02	amplifier
MIT, Cambridge	9.3	0.02	33	TE_{11}^c	0.1	10	6	0.18	0.0055	Electrostatic	0.02	amplifier
[187,267-270]	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 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
[271,272]	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.[243]	95	0.2	100		10	4		2.5	0.1	Pulse Line	0.25	oscillator
RI, Moscow [273]	6-25	0.03	48	TE_{11}^c/TM_{01}^c	10	1.7		0.6	1	Pulse Line	2	spon.emiss.
SIAE, Chengdu [274]	37	0.125	34.5	TE_{11}^c	7.6	5.4		0.5	0.28	Electrostatic	0.015	oscillator
SIOFM, Shanghai [275,276]	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	spon.emiss.
TRW, Redondo Beach [277]	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	0.002	6.9	3	0.29	0.0001	Electrostatic	10	amplifier
UNIV. Liverpool [278]	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 [279,280]	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[281]	120-880	0.15	71.4		0.027	0.5		2-6	0.002	Electrostatic	1-20	oscillator
UNIV. Strathclyde,IAP[282]	32.5	0.13	23	TE_{11}^c	0.5	5.0		0.3	0.03	Pulse Line	0.1	oscillator
UNIV. Tel Aviv [283]	4.5	0.03	44.4	TE_{10}^r	0.0035	6.3		0.07	0.0008	Electrostatic	3	oscillator
U.TelAviv,Weizm.Inst.[284]	100.5	0.2	44.4		0.001	0.05		1.4	0.0014	Electrostatic	2	oscillator
UNIV. Twente [285]	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

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

mm-wave frequency	130-260 GHz
mm-wave output power	1 MW
Electron energy	1.35-2 MeV
Electron beam current	12 A
Electron loss current	< 20 mA
Normalised beam emittance (xx')	50 π mm mrad
Pulse length	100 ms
Duty cycle	10^{-3}
Overall efficiency (mains to P_{mmw})	> 50 %
Linear gain	7 - 10
Gain in saturation	3.5
Waveguide mode	HE_{11}
Type of waveguide	rectangular corrugated
Cross section of primary waveguide	15*20 mm^2
Separation mmw beam, electron beam via stepped waveguide	
Undulator period	40 mm
Undulator gap	25 mm
Peak undulator field, section 1	0.2 T
Number of full cells, section 1	20
Gap between undulator sections	60 mm (adjustable)
Peak undulator field, section 2	0.16 T
Number of full cells, section 2	14
Total number of cells (incl. matching)	38
Length of undulator	1.58 m

Table XXVI: Design parameters of the FOM-FEM [242].

13 Comparison of Gyrotron and FEM for Nuclear Fusion

Table XXVII 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, 0.1-1.0 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 (35 %)	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
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/3 s (coax. 1.2 MW / 1 m.s)	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. 60 %)	60 %
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 XXVII: Comparison of parameters and features of gyrotron oscillators and FEMs for ECRH.

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