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

Update 2010

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Karlsruhe Institute of Technology

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by
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STATE-OF-THE-ART OF HIGH POWER GYRO-DEVICES AND FREE ELECTRON MASERS UPDATE 2010

Abstract

Gyrotron oscillators (gyromonotrons) are mainly used as high power millimeter wave sources for electron cyclotron resonance heating (ECRH), electron cyclotron current drive (ECCD), stability control and diagnostics of magnetically confined plasmas for generation of energy by controlled thermonuclear fusion. The maximum pulse length of commercially available 140 GHz, megawatt-class gyrotrons employing synthetic diamond output windows is 30 minutes (CPI and European KIT-CRPP-CEA-TED collaboration). The world record parameters of the European megawatt-class 140 GHz gyrotron are: 0.92 MW output power at 30 min. pulse duration, 97.5% Gaussian mode purity and 44% efficiency, employing a single-stage depressed collector (SDC) for energy recovery. A maximum output power of 1.5 MW in 4.0 s pulses was generated with the JAEA-TOSHIBA 110 GHz gyrotron. The Japan 170 GHz ITER gyrotron achieved 1 MW, 800 s at 55% efficiency and holds the energy world record of 2.88 GJ (0.8 MW, 60 min.) and the efficiency record of 57% for tubes with an output power of more than 0.5 MW. The Russian 170 GHz ITER gyrotron achieved 0.8 MW with a pulse duration of 1000 s and 55% efficiency. The short-pulse pre-prototype tube of the European 2 MW, 170 GHz coaxial-cavity gyrotron for ITER achieved at KIT the record power of 2.2 MW at 30% efficiency (without SDC) and 96% Gaussian mode purity. Russian gyrotrons for plasma diagnostics or spectroscopy applications deliver P_{out} = 40 kW with τ = 40 µs at frequencies up to 650 GHz ($\eta \geq 4\%$), P_{out} = 5.3 kW at 1 THz (η = 6.1%), and P_{out} = 0.5 kW at 1.3 THz (η = 0.6%). 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} = 4-50 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 gyrotrons for plasma diagnostics. In addition, this work gives a short overview of the present development status of coaxial-cavity multi-megawatt gyrotrons, gyrotrons for technological and spectroscopy applications, relativistic gyrotrons, quasi-optical gyrotrons, fast- and slow-wave cyclotron autoresonance masers (CARMs), gyroklystrons, gyro-TWT amplifiers, gyrotwystron amplifiers, gyro-BWO's, gyropeniotrons, magnicons, gyroharmonic converters, free electron masers (FEMs) and of vacuum windows for such high-power mm-wave sources. The highest CW powers produced by gyroklystrons and FEMs are, respectively, 10 kW (94 GHz) and 36 W (15 GHz). The IR FEL at the Thomas Jefferson National Accelerator Facility in the USA obtained a record average power of 14.2 kW at a wavelength of 1.6 µm. The THz FEL (NOVEL) at the Budker Institute of Nuclear Physics in Russia obtained a maximum average power of 0.5 kW in the wavelength range 40-235 µm (7.49-1.28 THz).

As a result of the excellence initiative launched by the Federal Government of Germany and the German Science Foundation, the Karlsruhe Institute of Technology (KIT) has been founded. Being a merger of Forschungszentrum Karlsruhe GmbH and Universität Karlsruhe (TH), KIT is a University of the State of Baden-Württemberg and a National Laboratory of the Helmholtz Association. It focuses on a knowledge triangle that links the tasks of research, teaching, and innovation.

Please send corrections, completions and supplements to
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STATUS DER ENTWICKLUNG VON HOCHLEISTUNGS-GYRO-RÖHREN UND FREI-ELEKTRONEN-MASERN STAND: ENDE 2010

Zusammenfassung

Gyrotronoszillatoren (Gyromonotrons) werden vorwiegend als Hochleistungsmillimeterwellenquellen für Elektron-Zyklotron-Resonanzheizung (ECRH), Elektron-Zyklotron-Stromtrieb (ECCD), Stabilitätskontrolle und Diagnostik von magnetisch eingeschlossenen Plasmen zur Erforschung der Energiegewinnung durch kontrollierte Kernfusion eingesetzt. Die maximale Pulslänge von kommerziell erhältlichen 140 GHz, 1 Megawatt Gyrotrons mit Austrittsfenstern aus künstlichem Diamant ist 30 min. (CPI und Europäische KIT-CRPP-TED-CEA Zusammenarbeitsgemeinschaft). Die Weltrekordparameter des europäischen 140 GHz-Megawatt-Gyrotrons sind: 0,92 MW Ausgangsleistung bei 30 min. Pulslänge, 97,5% Gaußsche Modenreinheit und 44% Wirkungsgrad mittels eines Kollektors mit einstufiger Gegenspannung (SDC) zur Energierückgewinnung. Eine maximale Ausgangsleistung von 1,5 MW bei 4,0 s Pulslänge wurden mit dem JAEA-TOSHIBA 110 GHz Gyrotron erzeugt. Das japanische 170 GHz ITER-Gyrotron erreichte 1 MW, 800 s bei 55% Wirkungsgrad und hält den Energieweltrekord mit 2,88 GJ (0,8 MW, 60 min.) und den Wirkungsgradrekord mit 57% für Röhren mit einer Ausgangsleistung höher als 0,5 MW. Das russische 170 GHz ITER-Gyrotron erreichte 0,8 MW bei 1000 s Pulslänge und 55% Wirkungsgrad. Das Kurzpuls-Vorprototyp-Gyrotron des europäischen 2 MW, 170 GHz ITER Gyrotrons mit koaxialem Resonator erzielte am KIT die Rekordleistung von 2,2 MW bei 30% Wirkungsgrad (ohne SDC) und 96% Gaußscher Modenreinheit. Russische Gyrotrons zur Plasmadiagnostik oder für spektroskopische Anwendungen arbeiten bei Frequenzen bis zu 650 GHz bei P_{out} = 40 kW und τ = 40 µs ($\eta \geq 4\%$), P_{out} = 5,3 kW bei 1 THz (η = 6,1%) und P_{out} = 0,5 kW bei 1,3 THz (η = 0,6%). Gyrotronoszillatoren finden jedoch auch in der Materialprozeßtechnik erfolgreich Verwendung. Dabei werden Röhren mit folgenden Parametern eingesetzt: $f \geq 24$ GHz, P_{out} = 4-50 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 Gyrotrons zur Plasmadiagnostik eingegangen. Außerdem wird auch kurz über den neuesten Stand der Entwicklung von Multimegawatt-Gyrotrons mit koaxialem Resonator, Gyrotrons für technologische und spektroskopische Anwendungen, relativistischen Gyrotrons, quasi-optischen Gyrotrons, Zyklotron-Autoresonanz-Masern (CARMs) mit schneller oder langsamer Welle, Gyroklystrons, Gyro-TWT-Verstärkern, Gyrotwystron-Verstärkern, Gyro-Rückwärtswellenoszillatoren (BWOs), Gyro-Peniotrons, Magnicon-Verstärkern, Gyro-Harmonische-Konvertoren, Frei-Elektronen-Masern (FEM) und von Vakuumfenstern für solche Hochleistungsmillimeterwellenquellen berichtet. Die höchsten von Gyroklystrons und FEMs erzeugten CW-Leistungen sind 10 kW (94 GHz) bzw. 36 W (15 GHz). Der IR FEL der Thomas Jefferson National Accelerator Facility in den USA erreichte eine Rekord-Durchschnitts-Leistung von 14,2 kW bei einer Wellenlänge von 1,6 µm. Der THz FEL (NovoFEL) am Budker Institute of Nuclear Physics in Russland erzielte die maximale Durchschnittsleistung von 0,5 kW im Wellenlängenbereich 40-235 µm (7,49-1,28 THz).

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Bitte schicken Sie Korrekturen, Vervollständigungen und Ergänzungen an
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1 Introduction

The possible applications of gyrotron oscillators and other electron cyclotron maser (ECM) fast-wave devices span a wide range of technologies [1-5]. 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 applications for magnetic confinement fusion studies, such as lower hybrid current drive (1-8 GHz), electron cyclotron resonance heating and current drive (28-170 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 mm-wave 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, ECR ion sources, submillimeter-wave and THz spectroscopy, materials processing and plasma chemistry.

Most work on ECM devices has investigated the conventional gyrotron oscillator (gyromonotron) [6-21] in which the wave vector of the radiation in an open-ended, irregular cylindrical waveguide cavity is almost transverse to the direction of the applied magnetic field, resulting in radiation near the electron cyclotron frequency or at one of its harmonics. Long pulse and CW gyrotron oscillators delivering output powers of 0.1-1.0 MW at frequencies between 28 and 170 GHz have been used very successfully in thermonuclear fusion research for plasma ionization and start-up, electron cyclotron resonance heating (ECRH) and local current density profile control by noninductive electron cyclotron current drive (ECCD) at system power levels up to 4.5 MW.

ECRH has become a well-established heating method for both tokamaks [22-39] and stellarators [39-51]. The confining magnetic fields in present day fusion devices are in the range of B_o=1-3.6 Tesla. As fusion machines become larger and operate at higher magnetic field ($B_o \cong 6$T) and higher plasma densities in steady state, it is necessary to develop CW gyrotrons that operate at both higher frequencies and higher mm-wave output powers. The requirements of the 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 40 MW at frequencies between 140 GHz and 170 GHz [19,21,23,29,37,40-47,52-58]. 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 1 MW per tube, CW [19,21], and 2 MW coaxial-cavity gyrotrons [58,59] 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 [17,29,60]. Frequency tuning has been shown to be possible on quasi-optical Fabry-Perot cavity gyrotrons [61,62] as well as on cylindrical cavity gyrotrons with step tuning (different operating cavity modes) [63-82].

This work reports on the status and future prospects of the development of gyrotron oscillators and RF vacuum windows for ECRH and ECR plasma sources for generation of multi-charged ions and soft X-rays [83-87] (Tables II-XII) but also refers to the development of very high frequency gyromonotrons for active plasma diagnostics [88-107], high-frequency sub-millimeter wave spectroscopy [108-139] and medical applications [140-141] (Tables XIII-XVI) and of quasi-optical gyrotrons (Table XX).

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 [1-5,142-154]. 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 2^{nd} harmonic of the electron cyclotron frequency), low anode voltage, high efficiency and long lifetime are under development. Mitsubishi in Japan and Gycom in Russia are also employing permanent magnet systems [149,152-154,155-161]. The state-of-the-art in this area of gyrotrons for technological applications is summarized in Table XVII.

The next generation of high-energy physics accelerators and the next frontier in understanding of elementary particles is based on the supercollider. For normal-conducting linear electron-positron colliders that will reach center-of-mass energies of > 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 [162-164]. 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 [165-173]. Therefore this report gives an overview of the present development status of relativistic gyrotrons (Tables XVIII and XIX), fast- and slow-wave cyclotron autoresonance masers (CARM) (Tables XXI and XXII), gyroklystrons (Table XXIII and XXIV), gyrotron travelling wave tube amplifiers (Gyro-TWT) (Tables XXV and XXVI), gyrotwystrons (Table XXVII), peniotrons and gyropeniotrons (Tables XXIX and XXX) and magnicons (Table XXXI) for such purposes as well as of free electron masers (FEM) (Table XXXII) and broadband gyrotron backward wave oscillators (Gyro-BWO) (Table XXVIII) for use as drivers for FEM amplifiers.

The present report updates and supplements the experimental achievements in the development of gyro-devices and free electron masers reviewed in [3-5,20,21,51-56], in KfK Report 5235 (Oct 1993), FZKA Reports 5564 (Apr 1995), 5728 (Mar 1996), 5877 (Feb 1997), 6060 (Feb 1998), 6224 (Jan 1999), 6418 (Feb 2000), 6588 (Mar 2001), 6708 (Feb 2002), 6815 (Feb 2003), 6957 (Feb 2004), 7097 (Feb 2005), 7198 (Feb 2006), 7289 (Feb 2007), 7392 (Mar 2008), 7467 (Apr 2009) and KIT Scientific Report 7540 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 reinforce 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 [15,18,174]

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

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

In the electron cyclotron maser (ECM), electromagnetic energy is radiated by relativistic electrons gyrating in an external longitudinal magnetic field. In this case, the effective frequency Ω corresponds to the relativistic electron cyclotron frequency:

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

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

In the case of a spatially periodic magnetic or electric field (undulator/wiggler), the transverse oscillation frequency 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,

$$\Omega_b = k_w v_z \quad , \quad k_w = 2\pi/\lambda_w \qquad (3)$$

The operating frequency of such devices, an example of which is the free electron maser (FEM) [175-179], 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 since the use of large waveguide or cavity cross sections reduces wall losses and breakdown restrictions, as well as permitting the passage of larger, higher power electron beams. It also relaxes the constraint that the electron beam in a single cavity can only remain in a favourable RF phase for half of a RF period (as in klystrons and other devices employing transition radiation). In contrast with klystrons, the reference phase for the waves in fast wave devices is the phase of the electron oscillations. Therefore, the departure from the synchronous condition, which is given by the transit angle $\theta = (\omega - k_z v_z - s\Omega)L/v_z$, can now be of order 2π or less, even in cavities or waveguides that are many wavelengths long.

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 [6,180]: Richard Twiss in Australia [181], Jürgen Schneider in the US [182] and Andrei Gaponov in Russia [183]. A short note on the possibility to use the rotational energy of a helical electron beam for microwave generation was published by the German Hans Kleinwächter in 1950 [184]. 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 [6,180,185]. 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 [186] (where the term "electron cyclotron maser" was apparently coined) and in Russia [187].

Many configurations can be used to produce coherent radiation based on the ECM instability. The departure point for designs based on a particular concept is the wave-particle interaction. Dispersion diagrams, also called ω-k_z plots or Brillouin diagrams [1,188-194], 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):

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

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

3.1 Gyrotron Oscillator and Gyroklystron Amplifier

Gyrotron oscillators (gyrotrons) were the first ECMs to undergo major development. In September 1964 scientists at IAP Nizhny Novgorod operated the first gyrotron (mode: TE_{101} rectangular cavity, power: 6 W, CW) [15]. 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 [6-14].

Gyrotron oscillators and gyroklystrons are devices which usually utilize only weakly relativistic electron beams (V_o < 100 kV, γ < 1.2) with high transverse momentum (pitch angle $\alpha = v_\perp/v_z > 1$) [176-179]. The wavevector of the radiation in the cavity is almost transverse to the direction of the external magnetic field ($k_\perp >> k_z$, and the Doppler shift is small) resulting, according to eqs. (1) and (2), in radiation near the electron cyclotron frequency or one of its harmonics:

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

In the case of cylindrical cavity tubes (see Figs. 1 and 2) the operating mode is close to cutoff ($v_{ph} = \omega/k_z >> c$) and the frequency mismatch $\omega - s\Omega_c$ is small but positive in order to achieve correct phasing, i.e. keeping the electron bunches in the retarding phase [188-194]. 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. Quasi-optical gyrotrons employ a Fabry-Perot mirror resonator perpendicular to the electron beam, also providing $k_\perp >> k_z$ (Fig. 2). By variation of the magnetic field, a sequence of discrete modes can be excited. The frequency scaling is determined by the value of B_o/γ. Modern high-power high-order volume mode CW gyrotron oscillators for fusion plasma applications employ an internal quasi-optical mode converter with lateral microwave output [192-201] and a single-stage depressed collector (SDC) for energy recovery (Tables II-VIII) (Fig.5). Cavity expansion due to ohmic wall heating and electron beam space charge neutralization reduce the operating frequency by a few hundred MHz [202]. Cyclotron harmonic operation reduces the required magnetic field for a given frequency by the factor s. However, the measured efficiencies for gyrotrons operating at higher harmonics (s = 2 and 3) are lower than those operating at the fundamental frequency [6-14,156-161,188-194].

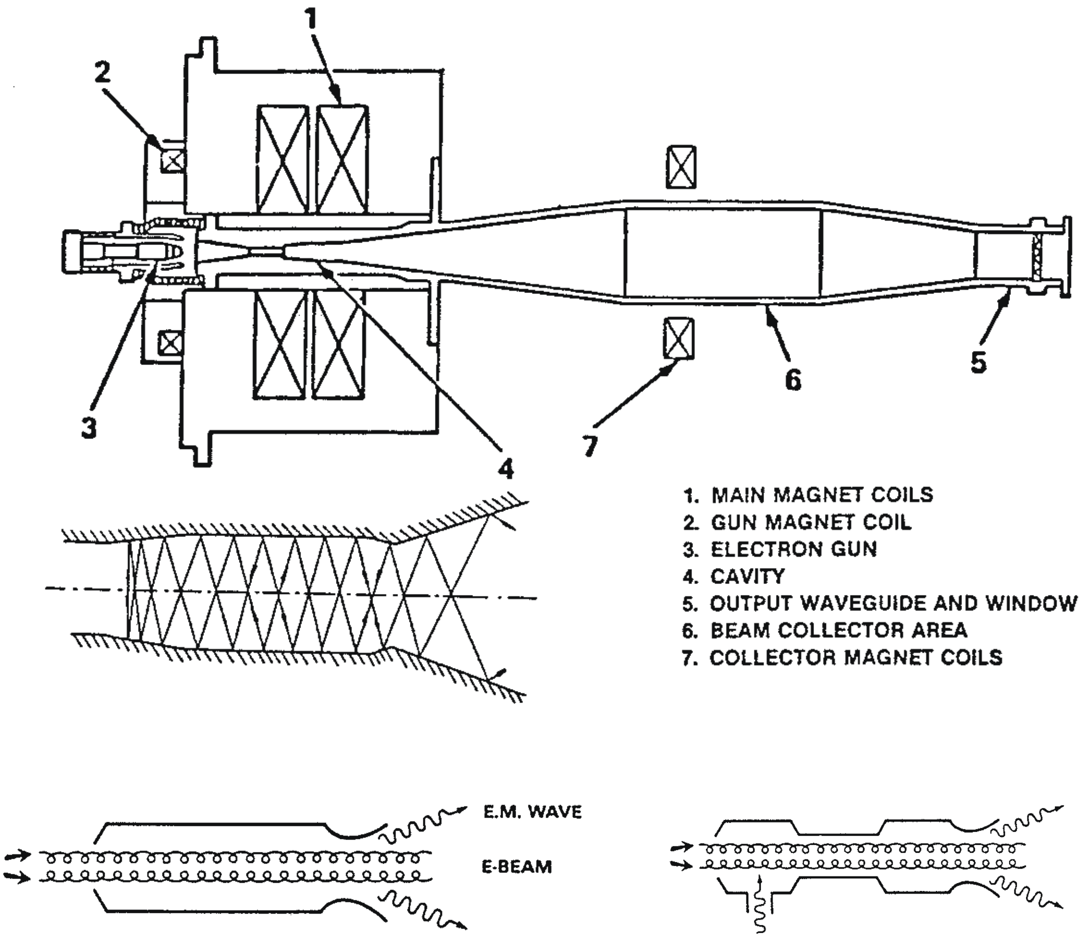


Fig. 1: Schematic of VARIAN CW gyrotron oscillator [11,16] and scheme of irregular waveguide cavities of gyromonotron oscillator (left) and gyroklystron amplifier [189,190].

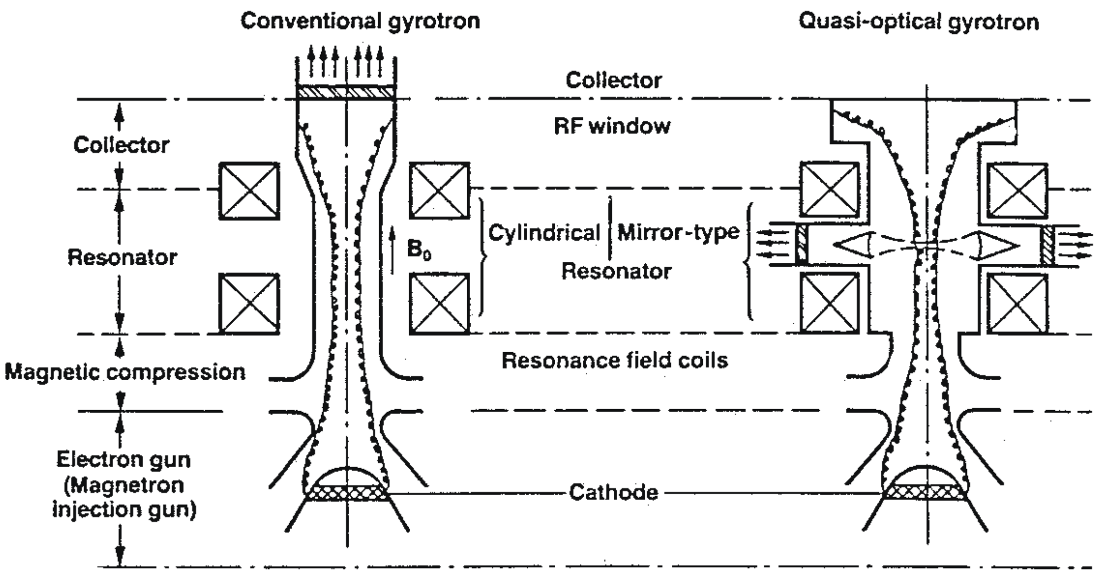


Fig. 2: Principle of a conventional gyrotron with cylindrical resonator and of a quasi-optical gyrotron with mirror resonator [61,62].

At low voltages, the number of electron orbits required for efficient bunching and deceleration of electrons can be large, which means that the resonant interaction has a narrow bandwidth, and that the RF field may have moderate amplitudes. In contrast with this, at high voltages, electrons should execute only about one orbit. This requires correspondingly strong RF fields, possibly leading to RF breakdown, and greatly broadens the cyclotron resonance band, thus making possible an interaction with many parasitic modes.

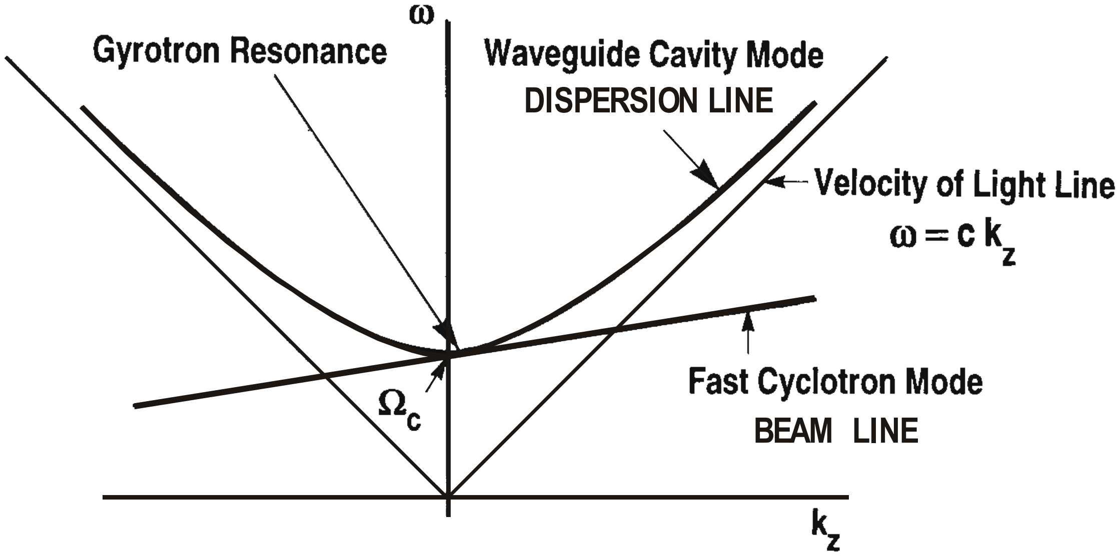


Fig. 3: Dispersion diagram of gyrotron oscillator (fundamental resonance).

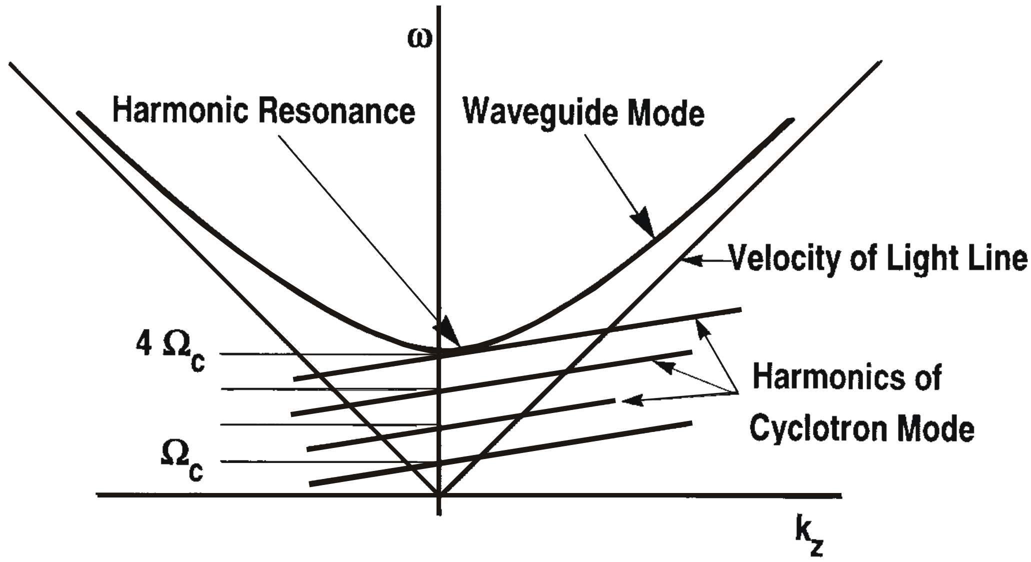


Fig. 4: Dispersion diagram of harmonic frequency gyrotron oscillator.

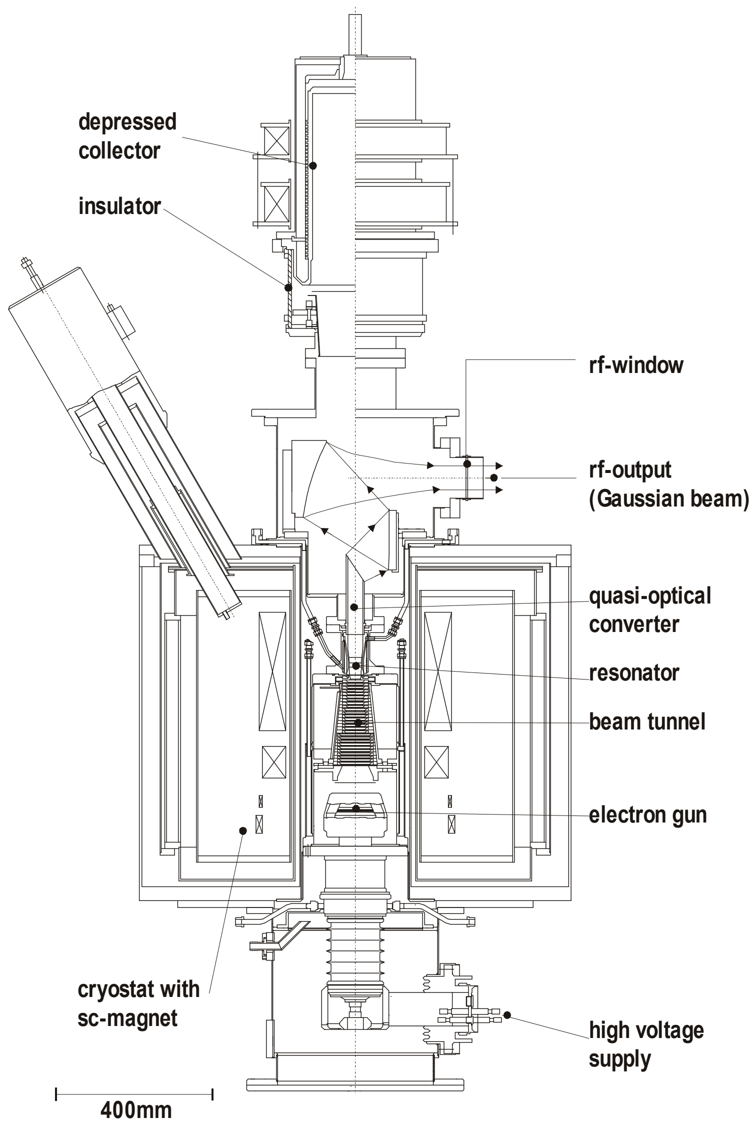


Fig. 5: Schematic layout of modern high-order volume mode gyrotron with quasi-optical mode converter and single-stage depressed collector.

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-shift 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 [15,174]. Fig. 6 shows how the Brillouin diagram of the fast cyclotron wave changes during the autoresonance

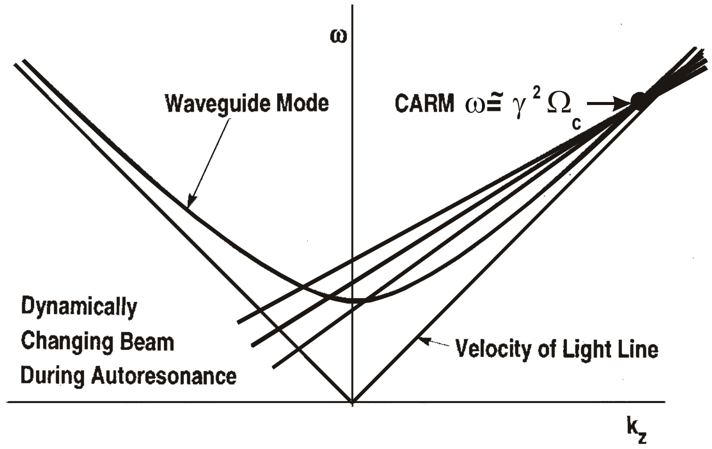
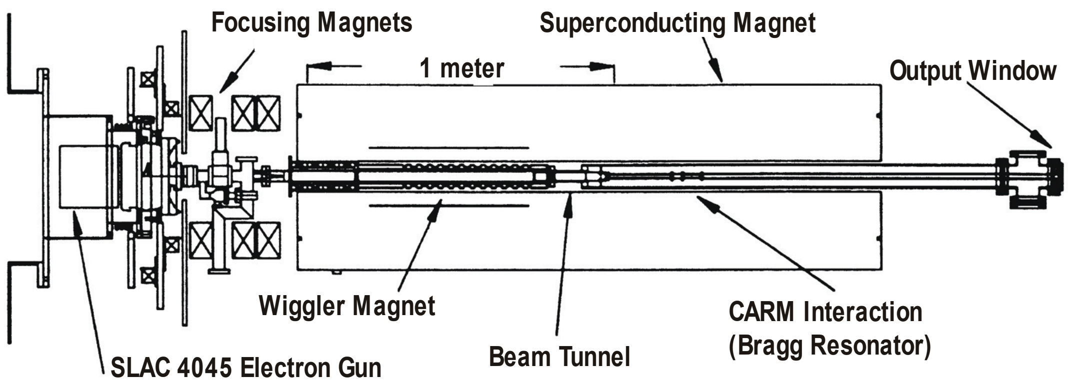


Fig. 6: Dispersion diagram of the cyclotron autoresonance maser (CARM).

interaction such that the working frequency ω remains constant even though both Ω_c and v_z are changing. The CARM interaction corresponds to the upper intersection and is based on the same instability mechanism as that of the gyrotron but operated far above cutoff. The instability is convective, so feedback, e.g. by a Bragg resonator (see Fig. 7) [174] 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. 6. 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.



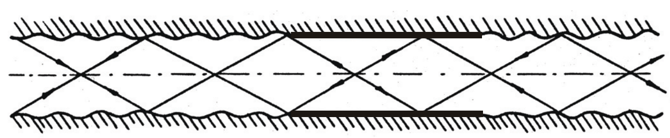


Fig. 7: Schematic of the long-pulse MIT CARM oscillator experiment [203] and scheme of a Bragg resonator [174].

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% [174,203].

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 [204-207], 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. 8) 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 velocity of the waveguide mode is nearly equal to v_z. In the gyro-TWT regime

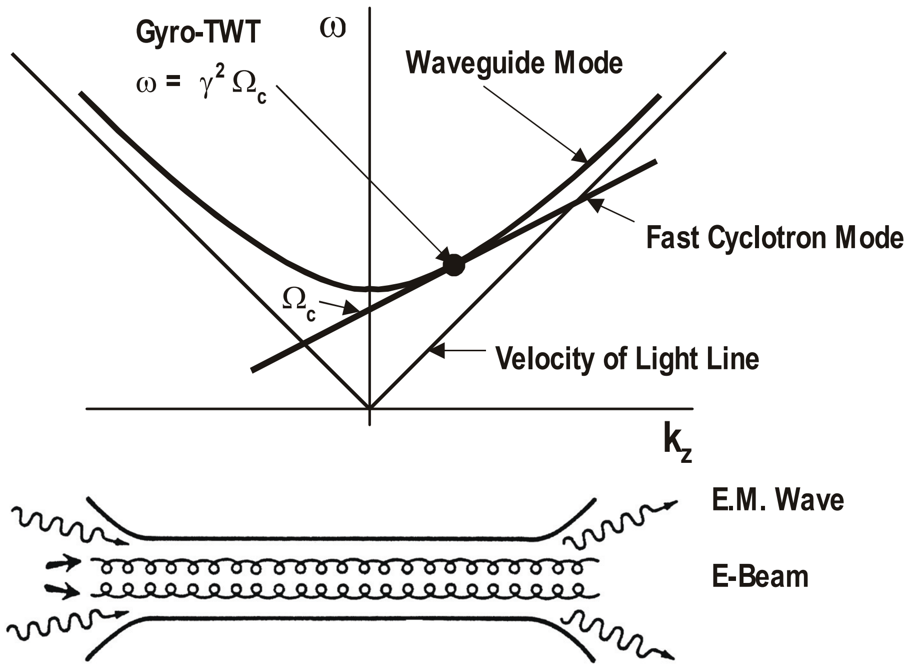


Fig. 8: Dispersion diagram and scheme of interaction circuit of Gyro-TWT amplifier.

($\omega/k_z >> c$), 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. Advanced devices employ tapered magnetic field and interaction circuit as well as two partially loaded stages in order to optimize the beam-wave interaction along the waveguide [208-211].

The sensitivity to velocity spread can be strongly reduced by coupling between the second harmonic cyclotron mode of a gyrating electron beam and the radiation field in the region of near infinite phase velocity over a broad bandwidth by using a cylindrical waveguide with a helical corrugation on its inner surface (coupled-modes gyro-TWT) [212,213].

The gyrotwystron [6], 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 has broader bandwith and can mitigate the problem of microwave breakdown at high power levels, since the microwave energy density in the output waveguide can be much smaller than in an output cavity. The inverted gyrotwystron is a device consisting of the input waveguide, drift section, and output cavity [214]. 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. 9) then an absolute instability (internal feedback) with a "backward wave" occurs. In the gyro-BWO the frequency of operation is now governed by the slope of the line, which is a function of v_z, and

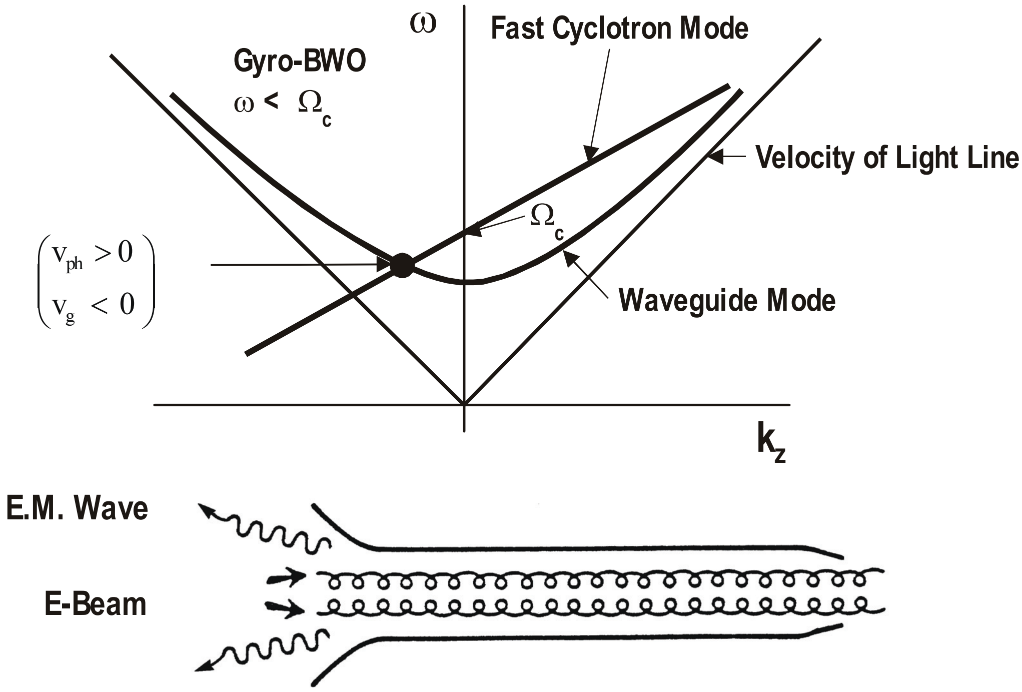


Fig. 9: Dispersion diagram and scheme of interaction circuit of Gyro-BWO.

thus of the beam acceleration voltage V_o. Consequently, just as in the case of slow-wave BWOs (e.g. carcinotron), the frequency of oscillations can be continuously changed very fast over a broad range, using V_o in place of B_o. However, 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, twystron and BWO [6]. 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 sections of klystron-type and twystron-type devices). This analogy suggests the correspondence between conventional linear-beam (O-type) devices and various types of gyro-devices. Table 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) [6]. 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.

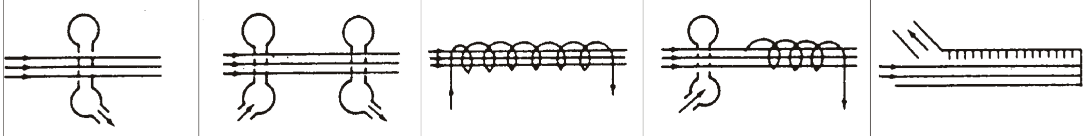
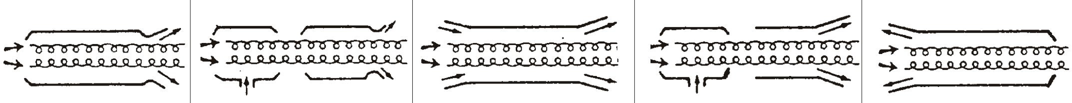
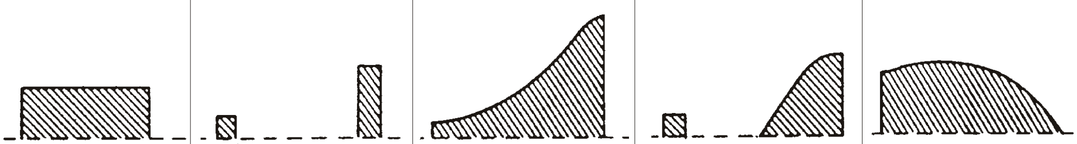
"0" TYP DEVICES	 MONOTRON	KLYSTRON	TWT	TWYSTRON	BWO
TYPE OF GYRO-DEVICE	 GYRO-MONOTRON	GYRO-KLYSTRON	GYRO-TWT	GYRO-TWYSTRON	GYRO BWO
MODEL RF-FIELD STRUCTURE					
MODEL ORBITAL EFFICIENCY	0.42	0.34	0.7	0.6	0.2

Table I: Overview of gyro-devices and comparison with corresponding conventional linear-beam (O-type) devices [6].

In Tables XIIIb, XVIII, XIX, XXIX and XXX 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 (LOG) employs an axis-encircling electron beam in which the trajectory of each electron takes it around the axis of the cylindrical interaction region [188,215]. For the operating modes TE_{mn} a strong selection rule is valid: m = s in eq. (5). 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 [189-192,216].

4 Magnicons and Gyroharmonic Converters

The magnicon is a member of the class of scanning-beam amplifier tubes [13,217,218]. It is a magnetized device that uses a fast-wave output cavity. Therefore, it can also be grouped with gyro-devices in which electrons gyrating in an external magnetic field emit bremsstahlung radiation near the cyclotron resonance. In the earliest version of the magnicon, an electron beam is deflected in the unmagnetized input cavity, using a rotating TM_{110} mode and after an also unmagnetized drift space, the deflected beam is spun up to high transverse momentum by entry into a strong magnetic field at the entrance of the output cavity.

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

Recently, higher perveance versions of the magnicon have been developed [218], in which a fully magnetized electron beam is spun up to a high transverse momentum in a sequence of deflection cavities containing synchronously rotating TM_{110} modes, the first driven by an external RF source (Fig. 10). In addition, the output cavity can operate in the *m*th harmonic of the drive frequency by using TM_{m10} modes with $m > 1$, permitting extension of magnicon operation to higher operating frequencies. Again the point of injection of the beam into the output cavity, as well as the entry gyrophase, rotate synchronously with a rotating RF mode of the output cavity. This makes possible much higher efficiencies than in most other gyro-devices. The key to the efficiency of these new magnicon designs is to spin the beam up to high transverse momentum ($\alpha > 1$) without producing large spreads in energy and gyrophase, so that the output cavity interaction will remain coherent over the entire ensemble of electrons, and not just synchronous in time. This requires great care in the design of the deflection cavities, in particular of the penultimate deflection cavity that produces more than half of the beam spin up. Since these spreads are generated by the fringing fields of the beam tunnel apertures in the deflection cavities and the output cavity, it also requires the use of a very small initial beam radius.

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

A similar "scanning-beam" device is the gyroharmonic converter in which dubbed "co-generation" arises from a near match in group and phase velocities between the input cavity TE_{11} mode at frequency ω and TE_{72} mode at frequency 7ω in a cylindrical waveguide [219]. This match allows efficient power transfer into the 7^{th} harmonic from a fundamental frequency wave that energizes an electron beam via cyclotron autoresonance acceleration (CARA). Theory indicates that high conversion efficiency can be obtained for a high quality beam injected into CARA, and when mode competition can be controlled.

Generation of 0.5 MW power (3 μs pulse duration, 5 % efficiency) at 8.57 GHz (3^{rd} harmonic of 2.856 GHz) in the TE_{31} mode has been observed in experiments using a 350 kV, 30 A electron beam [219-221].

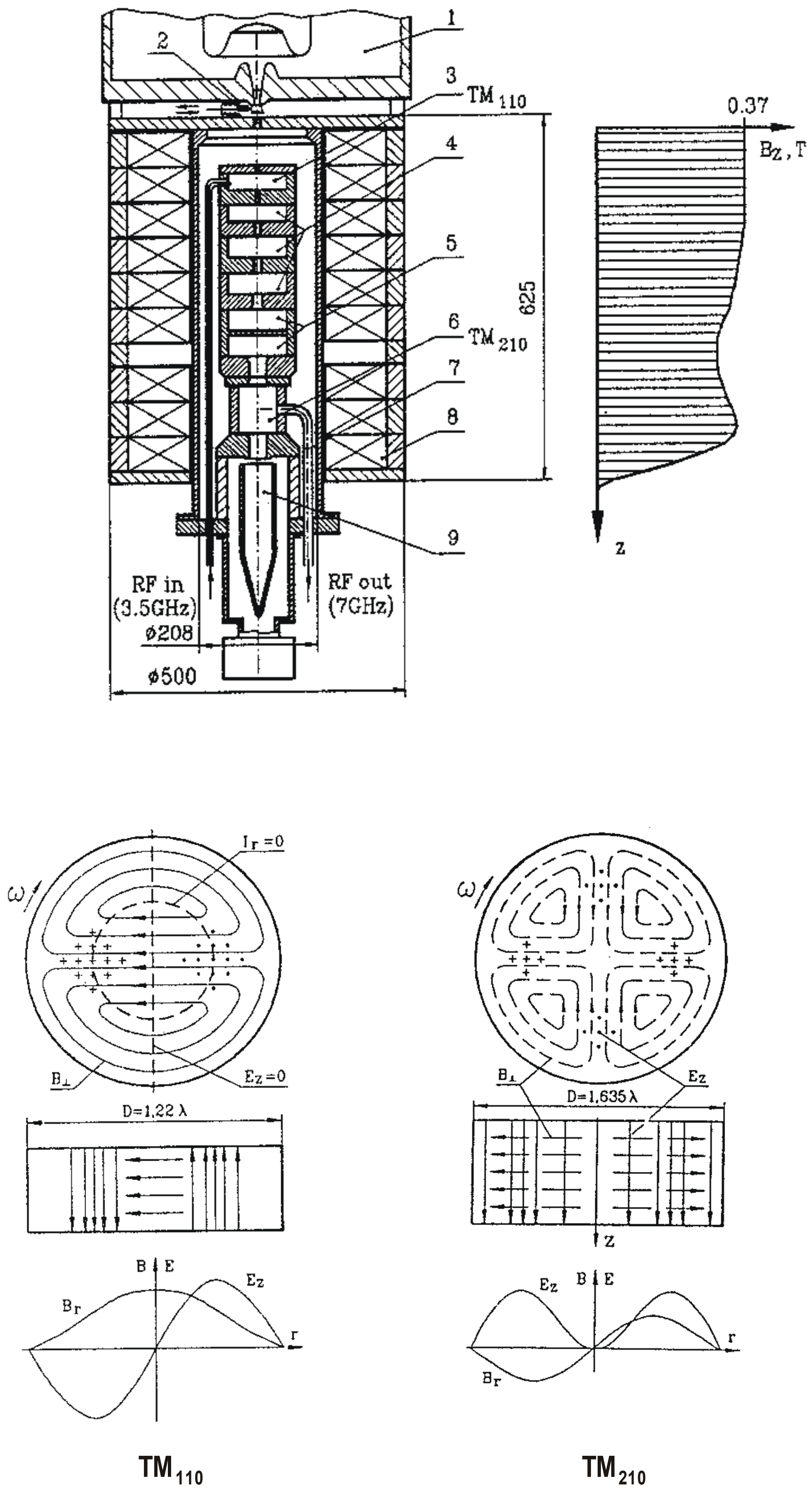


Fig. 10: Schematic layout of the magnicon: 1 – electron source; 2 – vacuum valve; 3 – drive cavity; 4 – gain cavity; 5 – penultimate cavity; 6 – output cavity; 7 – waveguide (x2); 8 – solenoid; 9 – collector [217].

5 Free Electron Masers

Free electron lasers (FELs) differ from the other high-power microwave sources considered in this report in that they have demonstrated output over a range of frequencies extending far beyond the microwave spectrum, well into the visible and ultraviolet range [174,179,189,190]. To achieve this spectral versatility, FELs exploit relativistic beam technology to upshift the electron "wiggle" frequency by an amount roughly proportional to γ^2 (see Fig. 11 and Section 2). In this respect, perhaps a more descriptive name is that coined by R.M. Phillips [222]: 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 [6,15,174]. The distinction between long wavelength free electron maser (FEM) ($\lambda \geq 0.5$ mm) and short wavelength FELs is natural because higher current and lower energy beams are typically employed in this regime and space-charge effects are more important. In particular, the dominant interaction mechanism is often coherent Raman scattering. Also, while short wavelength FELs excite optical modes, dispersion due to the beam dielectric effects and finite transverse dimensions in the drift tubes and cavities are important effects at longer wavelengths. A low power (3 W, 2 ms pulses) FEL operating at radio frequencies (FER) employing a 420 V, 0.2 A electron beam holds the world record for long wavelength ($f = 266$ MHz, $\lambda = 1.1$ m, $\lambda_w = 0.04$ m, $B_w = 0.04$ T) [223].

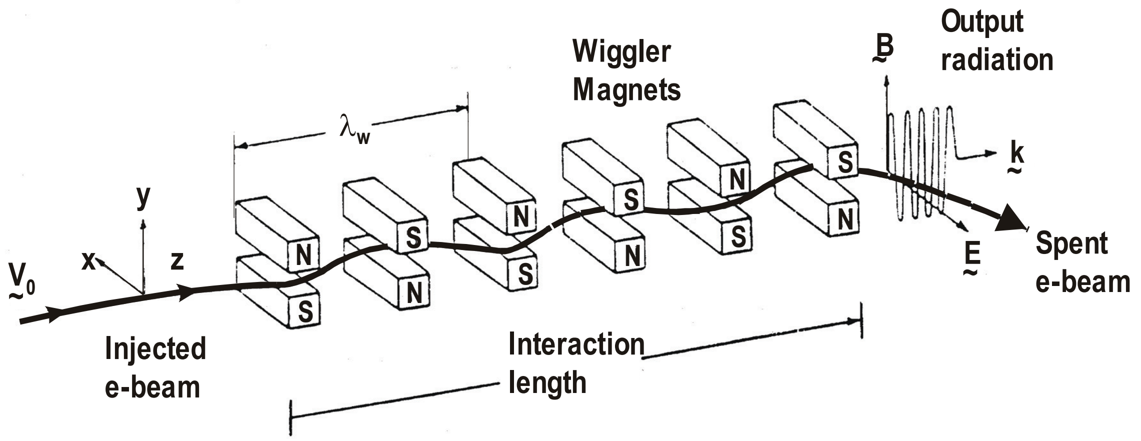


Fig. 11: The basis FEM configuration. Electrons in an injected electron beam undulate in the periodic magnetic field of the wiggler.

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 [4,224-235]. 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) and a multi-stage depressed collector are compatible with a high unit power at efficiencies around 50% if the electron beam interception could be maintained at an acceptable level. A survey of FEM development status (experiments) is presented in Tables XXXII and XXXIII. It is a great pity that the FOM-FEM project [224-234] was terminated in the autumn of 2001.

The highest CW power generated by a FEM is 36 W (15 Hz) [236] whereas the IR-FEL at the Thomas Jefferson National Accelerator Facility obtained a record average power of 10 kW at 1-14 μm (14.2 kW at 1.6 μm). A recirculated electron beam power of up to 1 MW (Energy Recovering Linac) has been demonstrated resulting in an overall efficiency of approximately 2% [237-243]. The average output power in the THz regime is 100 W.

The first stage of the Novosibirsk High Power Free Electron Laser (NovoFEL) had been commissioned in 2003. This THz-FEL generates coherent radiation, tunable in the range of 110-235 μm (2.73-1.28 THz), 60-117 μm and 40-80 μm at the first, second and third harmonics, respectively, with the corresponding maximum average output powers of 0.5 kW, 100 W and 30 W. The maximum peak power is 1 MW (bunch duration: 40-100 ps), the minimum relative linewidth is 0.3% [244,245].

The two-orbit energy recovery linac stage was assembled and commissioned in 2008. The first lasing of the two-stage THz-FEL was achieved in 2009, providing radiation in the wavelength range 40-80 μm at an average output power of 0.5 kW [246].

6 Gyrotron Oscillators and Microwave Vacuum Windows for Plasma Heating

Institution	Frequency [GHz]	Mode cavity	Mode output	Power [MW]	Efficiency [%]	Pulse length [s]
ABB, Baden [192,247]	8	TE_{01}	TE_{01}	0.35	35	0.5
	39	TE_{02}	TE_{02}	0.25	42	0.1
CPI[1], Palo Alto	8	TE_{21}	TE_{10}	0.5 (dual output)	33	1.0
[11,16,248-261]	28,35	TE_{02}	TE_{02}	0.2	37	CW
	53.2,56,60,70	$TE_{01/02}$	TE_{02}	0.23	37	CW
	70.15	$TE_{10,3}$	TEM_{00}	0.6	47 (SDC)	2.25
	84	$TE_{15,2}$	$TE_{15,2/4}$	0.5(0.9)	28	0.1(0.001)
	84	$TE_{15,4}$	TEM_{00}	0.56	44 (SDC)	2.0
	94.9	$TE_{6,2}$	TEM_{00}	0.12	50 (SDC)	CW
	95.3	$TE_{22,6}$	TEM_{00}	0.62 (1.72)	41 (33) (SDC)	15 (0.005)
CPI[1], NIFS	84	$TE_{15,3}$	TEM_{00}	0.5(0.4)	29	2.0(10.5)
Palo Alto, Toki				0.1	14	CW
[48,49,249-253,262-265]				0.59(0.25)	41 (SDC)	0.001(0.2)
				0.25	32 (SDC)	0.2
GYCOM, IAP	5	TE_{01}	TE_{01}	0.23	26	0.1
Nizhny Novgorod	28	TE_{42}	TEM_{00}	0.5	36	0.5
[12,64,65,77-87,266-276]	37.5	TE_{62}	TEM_{00}	0.5	35	0.1
	53.2	TE_{83}	TEM_{00}	0.5 (0.3)	40 (36)	0.1 (1.0)
	68 (70)	TE_{93}	TEM_{00}	0.5 (0.68)	50 (48) (SDC)	1.0 (3.0)
	75	TE_{94}	TEM_{00}	0.5	37	0.1
	75	$TE_{11,5}$	TEM_{00}	0.8	70 (SDC)	0.1
	82.5	$TE_{11,3}$	$TE_{11,3}$	1.0(1.5)	50(36)	0.0001
	82.7	$TE_{10.4}$	TEM_{00}	0.65	38	3.0
				0.65	53 (SDC)	3.0
				0.9	32	0.3
				0.2	52 (SDC)	CW
	84	$TE_{12.5}$	TEM_{00}	0.88	54 (SDC)	3.0
				0.5 (0.2)	50 (SDC)	10 (CW)
HUGHES, Torrance [189]	60	TE_{02}	TE_{02}	0.2	35	0.1
IAP, Nizhny Novgorod [277]	$25(2\Omega_c)$	TE_{03}	TE_{03}	0.8	40 (twin e-beam)	0.0001
IECAS, Beijing [278,279]	24.1	TE_{01}	TE_{01}	0.15	24	0.02
	$34.3(2\Omega_c)$	$TE_{02/03}$	TE_{03}	0.2	30	0.02
LAP/INPE, Sao Paulo [280]	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	88	$TE_{8,2}$	TEM_{00}	0.35	29	0.1
KYOTO UNIV. [281]						
NEC, Kawasaki [282]	35	TE_{01}	TE_{01}	0.1	30	0.001
NRL, Washington D.C.	35	TE_{01}	TE_{01}	0.15	31	0.02
[189,283]	35	TE_{04}	TE_{04}	0.475	38	0.001
	35	TE_{24}	TE_{24}	0.43	40	0.001
PHILIPS[2], Hamburg [284]	70	TE_{02}	TE_{02}	0.14	30	CW
SPbSTU, St. Petersburg	74.2	$TE_{12.3}$	$TE_{12,3}$	0.1	44	0.00005
KIT[3] Karlsruhe [285-292]						
THALES ED[4], Velizy	8	TE_{51}	TE_{51}	1.0	45	1.0
[192,293]	35	TE_{02}	TE_{02}	0.2	43	0.15
TOSHIBA, Otawara	28	TE_{02}	TE_{02}	0.2	35.7	0.075
[51,294-296]		$TE_{4,2}$	TEM_{00}	0.57	40	0.01
		$TE_{8,3}$	TEM_{00}	1.05 (0.8)	30 (40)	0.001
	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
	77	$TE_{18,6}$	TEM_{00}	1.5	38 (SDC)	2.0
				1.2	38 (SDC)	10.0
				0.3	36 (SDC)	900
UESTC, Chengdu [297-301]	$35(3\Omega_c)$	TE_{51}/TE_{52}	TE_{52}	0.147	10.2	0.0001 PM, 100 kg
	$70(2\Omega_c)$	TE_{02}/TE_{03}	TE_{03}	0.1	20	0.0001
	$94(2\Omega_c)$	TE_{02}/TE_{03}	TE_{03}	0.12	20.5	0.0001
	94	TE_{61}/TE_{62}	TE_{61}/TE_{62}	0.09	43	CW

SDC: Single-stage Depressed Collector
[1] Communications & Power Industries, formerly VARIAN, [2] formerly VALVO, [3] Karlsruhe Institute of Technology, formerly FZK, [4] formerly Thomson TE

Table II: Performance parameters of gyrotron oscillators for electron cyclotron resonance heating (ECRH) (28-95 GHz) and lower hybrid current drive (5-8 GHz) in plasmas for magnetic confinement fusion studies.

Institution	**Frequency [GHz]**	**Mode cavity**	**Mode output**	**Power [MW]**	**Efficiency [%]**	**Pulse length [s]**
CPI[1)], Palo Alto [11,249-253,302-316]	106.4($2\Omega_c$)	$TE_{02/03}$	TE_{03}	0.135	21	0.1
	106.4	$TE_{12,2}$	$TE_{12,2}$	0.4	30	0.1
	110	$TE_{15,2}$	$TE_{15,2}$	0.5	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}	1.28	42.3 (SDC)	0.001
				1.05	31	5.0
				0.6 (0.52)	31 (29 SDC)	10.0
				0.106	21	CW
KIT[2)], Karlsruhe [66-72,317-330]	117.9	$TE_{19,5}$	TEM_{00}	1.55	31	0.007
				1.55	49.5 (SDC)	0.007
	132.6	$TE_{9,4}$	$TE_{9,4}$	0.42	21	0.005
GYCOM-M (TORIY, IAP) Moscow, N. Novgorod [12,194,271,331-340]	110	$TE_{19,5}$	TEM_{00}	1.2	40	0.0001
				1.0	65(SDC)	0.0001
				0.93	36	2.0
				0.5	35	5.0
				0.35	33	10.0
GYCOM-N (SALUT, IAP) N. Novgorod [12,64,65,73-82,266-271, 341-345]	104	$TE_{18,7}$	TEM_{00}	0.98	46.5 (SDC)	0.5
	105	$TE_{17,6}$	TEM_{00}	0.84	48 (SDC)	10.0
	106.4	$TE_{15,4}$	TEM_{00}	0.5	33	0.2
	110	$TE_{15,4}$	TEM_{00}	0.5	33	1.0
	111.5	$TE_{19,6}$	TEM_{00}	1.0	32	0.0001
	129	$TE_{17,5}$	TEM_{00}	0.5	32	0.5
JAEA[3)], TOSHIBA Naka, Otawara [19,346-363]	110	$TE_{22,2}$	TEM_{00}	0.75	27.6	0.002
				0.61	30	0.05
				0.61	50 (SDC)	0.05
				0.42	48 (SDC)	3.3
				0.35	48 (SDC)	5.0
	110	$TE_{22,6}$	TEM_{00}	1.5	45 (SDC)	4.0
				1.0	38 (SDC)	31.0
	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
MITSUBISHI, Amagasaki [364,365]	120	$TE_{02/03}$	TE_{03}	0.16	25	0.06
	120	$TE_{15,2}$	$TE_{15,2}$	1.02	32.5	0.0002
				0.46	30	0.1
				0.25	30	0.21
THALES ED[4)], Velizy [192,293]	100	TE_{34}	TE_{34}	0.19	30	0.07
	110	TE_{93}	TE_{93}	0.42	17.5	0.002
	110	TE_{64}	TE_{64}	0.34	19	0.01
				0.39	19.5	0.21
THALES ED[4)], CEA,CRPP, KIT [366-376]	118	$TE_{22,6}$	TEM_{00}	0.7	37	0.01
				0.53	32	5.0
				0.35	23	111.0

SDC: Single-stage Depressed Collector
[1)] Communications & Power Industries, formerly VARIAN, [2)] formerly KfK, then FZK, [3)] formerly JAERI
[4)] formerly Thomson TE

Table III: Present development status of high frequency gyrotron oscillators for ECRH and stability control in magnetic fusion devices (100 GHz $\leq$ f $<$ 140 GHz, $\tau \geq$ 0.1 ms).

Institution	Frequency [GHz]	Mode cavity	Mode output	Power [MW]	Efficiency [%]	Pulse length [s]
CPI[1], Palo Alto	140	$TE_{02/03}$	TE_{03}	0.1	27	CW
[11,16,249-253,311-315,	140	$TE_{15,2}$	$TE_{15,2}$	1.04	38	0.0005
377-389]				0.32	31	3.6
				0.2 (0.4)	31	avg. (peak)
	140.2	$TE_{28,7}$	TEM_{00}	0.92	35 (SDC)	0.003
				0.9	33 (SDC)	1800
KIT[2], PHILIPS[3] [192,381]	140.8	TE_{03}	TE_{03}	0.12	26	0.4
KIT[2], Karlsruhe	140.2	$TE_{10,4}$	$TE_{10,4}$	0.69	28	0.005
[66-72,192,317-330,381-396]	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}	1.6	60 (SDC)	0.007
				2.1	53 (SDC)	0.001
	162.3	$TE_{25.7}$	TEM_{00}	1.48	35	0.007
				1.48	50 (SDC)	0.007
KIT[2], CRPP, THALES ED[4],	139.8	$TE_{28,8}$	TEM_{00}	1.0	50 (SDC)	12
CEA [20,45-47,56-58,369,				0.92	44 (SDC)	1800
397-426]						
GYCOM-M (TORIY, IAP)	140	$TE_{22,6}$	TEM_{00}	0.96	36	1.2
Moscow, N. Novgorod				0.54	36	3.0
[12,73-82,267-271,333-340,				0.26	36	10
345,427-456]				0.1	35	80
		(dual-beam	output)	2x0.37	30	3.0
				2x0.3	29	5.5
				2x0.165	28	10.0
	140	$TE_{22,8}$	TEM_{00}	1.7	42	0.0001
				1.2	68 (SDC)	0.0001
	140	$TE_{22,8}$	TEM_{00}	0.95	52(SDC)	10
	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
	170	$TE_{25,10}$	TEM_{00}	1.0	53 (SDC)	570
				0.8	55 (SDC)	1000
	170	$TE_{28,12}$	TEM_{00}	1.44	41 (SDC)	0.1
				2.1	35	0.0001
GYCOM-N (SALUT, IAP)	140	$TE_{22,6}$	TEM_{00}	0.8	32	0.8
N. Novgorod				0.88	50.5(SDC)	1.0
[12,64,65,266-269,275,				0.55	33	2.0
338-340,343,344,427,442]	140	$TE_{22,10}$	TEM_{00}	0.99	47 (SDC)	0.5
	158.5	$TE_{24,7}$	TEM_{00}	0.5	30	0.7
JAEA[5], TOSHIBA	170	$TE_{22,6}$	TEM_{00}	0.45	19	0.05
Naka, Otawara				0.25	19	0.4
[19,351-359,457-482]				0.25	32 (SDC)	0.4
	170.1	$TE_{31,8}$	$TE_{31,8}$	1.15	29	0.0004
	170	$TE_{31,8}$	TEM_{00}	1.3	32	0.003
				1.2	57 (SDC)	0.003
				1.0	55 (SDC)	800
				0.8	57 (SDC)	3600
	170	$TE_{31,12}$	TEM_{00}	1.56	27	0.1
NIFS, TOSHIBA	168	$TE_{31,8}$	TEM_{00}	0.52	19	1.0
Toki, Otawara				0.52	30 (SDC)	1.0
[48-51,265,483-484]						

SDC: Single-stage Depressed Collector
[1] Communications & Power Industries, formerly VARIAN, [2] formerly KfK, then FZK, [3] formerly VALVO,
[4] formerly Thomson TE, [5] formerly JAERI

Table IV: Present development status of high frequency gyrotron oscillators for ECRH and stability control in magnetic fusion devices (f ≥ 140 GHz, τ ≥ 0.1 ms).

Institution	Frequency [GHz]	Mode cavity	Mode output	Power [MW]	Efficiency [%]	Corrug.Cavity inner	Corrug.Cavity outer
KIT[1)] Karlsruhe	137.78	$TE_{27,16}$	$TE_{27,16}$	1.03	24.3	yes	no
[20,56-59,391-397,413,	139.96	$TE_{28,16}$	$TE_{28,16}$	1.17	27.2	yes	no*
485-507]			TEM_{00}	0.95	20	yes	no
Pulse length ≤ 100 ms				0.95	29(SDC)	yes	no
				(dual beam output)			
	142.02	$TE_{29,16}$	$TE_{29,16}$	1.04	24.4	yes	no
	138.70	$TE_{27,14}$	TEM_{00}	1.14	26.1	yes	no
	146.70	$TE_{28,15}$	TEM_{00}	1.13	25.6	yes	no
	156.90	$TE_{30,16}$	TEM_{00}	1.24	25.4	yes	no
	164.98	$TE_{31,17}$	$TE_{31,17}$	1.17	26.7	yes	no
			TEM_{00}	2.2	28	yes	no
				(single-beam output)			
				1.5	30	yes	no
				1.5	48 (SDC)	yes	no
	167.14	$TE_{32,17}$	TEM_{00}	1.22	25.6	yes	no
EGYC[2)] [508-530]	170	$TE_{34,19}$	TEM_{00}	2.2	30	yes	no
IAP, Nizhny Novgorod	45	$TE_{15,1}$	$TE_{15,1}$	1.25	43	no	no
[10,12,268,271,531-539]	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	33.5	yes	no*
				1.15	50 (SDC)	yes	no
			$TE_{76,2}$	1.17	35.2	yes	yes
			TEM_{00}	1.1	30	yes	no
				(dual-beam output)			
	224 ($2\Omega_c$)	$TE_{33,8}$	$TE_{33,8}$	0.1	11	yes	no
IAP, KIT[1)] Karlsruhe [485]	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 [540-542]	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, then FZK, * very similar cavity and tube design
2) EGYC is a collaboration among CRPP, Switzerland; KIT, Germany; HELLAS, Greece; CNR, Italy; ENEA Italy

Table V: Present experimental development status of short pulse (3 µs – 15 ms) coaxial cavity gyrotron oscillators.

Design studies for a 4 MW, 170 GHz coaxial-cavity gyrotron for future fusion reactors are currently being performed at KIT. The coaxial cavity operates in the $TE_{52,31}$ mode and the q.o. output coupler generates two fundamental Gaussian beams which leave the tube through two CVD-diamond windows [543,544].

Institution	Frequency [GHz]	Mode cavity	Mode output	Power [MW]	Efficiency [%]	Pulse length [s]
CPI[1], Palo Alto	8	TE_{21}	TE_{10}	0.4	26.6	0.0005
[248-261,306-315,377-380]	(dual rectangular waveguide output)			0.4	34.2 (SDC)	0.0005
	70.15	$TE_{10,3}$	TEM_{00}	0.6	47 (SDC)	2.25
	94.9	TE_{62}	TEM_{00}	0.12	50 (SDC)	CW
	95.3	$TE_{22,6}$	TEM_{00}	0.62 (1.4)	41 (SDC)	15 (0.005)
	110	$TE_{22,6}$	TEM_{00}	1.28	42.3 (SDC)	0.001
				0.52	29 (SDC)	10
	140.2	$TE_{27,8}$	TEM_{00}	0.92	35(SDC)	0.003
				0.9	33(SDC)	1800
CPI[1], NIFS	84	$TE_{15,3}$	TEM_{00}	0.5	29	2.0
Palo Alto, Toki [48-51,252]				0.59	41 (SDC)	0.001
				0.25	32 (SDC)	0.2
KIT[2], Karlsruhe	117.9	$TE_{19,5}$	TEM_{00}	1.55	49.5 (SDC)	0.007
[20,66-72,317-330,386-397]	140.2	$TE_{10,4}$	TEM_{00}	0.50	48 (SDC)	0.03
	140.5	$TE_{10,4}$	TEM_{00}	0.46	51 (SDC)	0.2
	140.1	$TE_{22,6}$	TEM_{00}	1.6	60 (SDC)	0.007
				2.1	53 (SDC)	0.001
	162.3	$TE_{25,7}$	TEM_{00}	1.48	50 (SDC)	0.007
KIT[2], CRPP, THALES ED[3],	139.8	$TE_{28,8}$	TEM_{00}	1.0	50 (SDC)	12
CEA [20,45-47,56-58,369, 397-426,]				0.92	43 (SDC)	1800
GYCOM-N (SALUT, IAP)	68 (70)	$TE_{9,3}$	TEM_{00}	0.5 (0.68)	50 (48) (SDC)	1.0 (3.0)
Nizhny Novgorod	75	$TE_{11,5}$	TEM_{00}	0.8	70 (SDC)	0.1
[269-271,273-276,334,335,	82.7	$TE_{10,4}$	TEM_{00}	0.65	38	3.0
340,342]				0.65	53 (SDC)	0.03
				0.2	52 (SDC)	CW
	84	$TE_{12,5}$	TEM_{00}	0.88 (0.2)	50 (SDC)	3.0 (CW)
	104	$TE_{18,7}$	TEM_{00}	0.98	46.5 (SDC)	0.5
	110	$TE_{19,5}$	TEM_{00}	1.0	65 (SDC)	0.0001
	140	$TE_{22,6}$	TEM_{00}	0.8	32	0.8
				0.88	50.5 (SDC)	1.0
	140	$TE_{22,10}$	TEM_{00}	0.99	47 (SDC)	0.5
GYCOM-M (TORIY, IAP)	140	$TE_{22,8}$	TEM_{00}	1.7	42	0.0001
Moscow, Nizhny Novgorod				0.95	52(SDC)	10
[73-82,275,437-456]	170	$TE_{25,10}$	TEM_{00}	1.4	35	0.0001
				1.0	62 (SDC)	0.0001
	170	$TE_{25,10}$	TEM_{00}	1.0	53 (SDC)	570
				0.8	55 (SDC)	1000
	170	$TE_{28,12}$	TEM_{00}	1.44	41 (SDC)	0.1
NRL, Washington D.C.	115	QOG	TEM_{00}	0.43	12.7 (SDC)	10^{-5}
[545]				0.20	16.1 (SDC)	10^{-5}
JAEA[4], TOSHIBA	110	$TE_{22,2}$	TEM_{00}	0.61	50 (SDC)	0.05
Naka, Otawara				0.35	48 (SDC)	5.0
[346-363,457-482]	110	$TE_{22,6}$	TEM_{00}	1.5	45 (SDC)	4.0
				1.0	38 (SDC)	31.0
	170	$TE_{22,6}$	TEM_{00}	0.25	19	0.4
				0.25	32 (SDC)	0.4
	170.2	$TE_{31,8}$	TEM_{00}	1.2	57 (SDC)	0.003
				1.0	55 (SDC)	800
				0.8	57 (SDC)	3600
NIFS, TOSHIBA	77	$TE_{18,6}$	TEM_{00}	1.0	32 (SDC)	5.0
Toki, Otawara [48-51,265,296,	168	$TE_{31,8}$	TEM_{00}	0.52	19	1.0
483,484]				0.52	30 (SDC)	1.0

SDC: Single-stage Depressed Collector; QOG: Quasi-Optical Gyrotron
[1] formerly VARIAN, [2] formerly KfK, then FZK, [3] formerly Thomson TE [4] formerly JAERI

Table VI: Present development status of high frequency gyrotron oscillators with conventional cylindrical or quasi-optical cavity and single-stage depressed collector (SDC) ($\tau \geq 10\ \mu s$).

Institution	Frequency [GHz]	Mode cavity	Mode output	Power [MW]	Efficiency [%]	Pulse length [s]	
KIT[1)], Karlsruhe	114.2	TE$_{18,5}$	TEM$_{00}$	0.85	23	0.001	
[66-72,322-325-330,	117.9	TE$_{19,5}$	TEM$_{00}$	1.0	27	0.001	
392-397,424-426]				1.55	49.5 (SDC)	0.007	optimized
	121.6	TE$_{20.5}$	TEM$_{00}$	1.0	27	0.001	
	125.3	TE$_{21,5}$	TEM$_{00}$	1.0	27	0.001	
	128.9	TE$_{22,5}$	TEM$_{00}$	0.9	24.5	0.001	
	132.6	TE$_{20,6}$	TEM$_{00}$	0.85	23	0.001	
	136.2	TE$_{21,6}$	TEM$_{00}$	0.9	24.5	0.001	
	140.1	TE$_{22,6}$	TEM$_{00}$	1.0	27	0.001	
				1.6	60 (SDC)	0.007	optimized
	143.7	TE$_{23.6}$	TEM$_{00}$	1.1	30	0.001	
	147.4	TE$_{24,6}$	TEM$_{00}$	1.1	30	0.001	
	151.2	TE$_{25,6}$	TEM$_{00}$	1.05	28.5	0.001	
	154.9	TE$_{23,7}$	TEM$_{00}$	0.95	26	0.001	
	158.5	TE$_{24,7}$	TEM$_{00}$	1.1	30	0.001	
	162.3	TE$_{25,7}$	TEM$_{00}$	1.0	27	0.001	
				1.48	50 (SDC)	0.007	optimized
	166.0	TE$_{26,7}$	TEM$_{00}$	1.0	26	0.001	
GYCOM, IAP	71.5	TE$_{10,5}$	TEM$_{00}$	0.8	56	0.15	3f-Gyrotron
Nizhny Novgorod	74.8	TE$_{11,5}$	TEM$_{00}$	0.8	56	0.15	with
[36,64,65,73-82,271,275,	78.1	TE$_{12,5}$	TEM$_{00}$	0.8	56	0.15	Brewster
340,343-345,449,450,546]							window
	121.5	TE$_{20,5}$	TEM$_{00}$	0.5	30	00001	
	140.0	TE$_{22,6}$	TEM$_{00}$	0.5	30	0.5	
	158.5	TE$_{24,7}$	TEM$_{00}$	0.5	30	0.7	
	105.1	TE$_{17,6}$	TEM$_{00}$	1.24	41.2	0.0001	
				0.83	49 (SDC)	10	
	111.7	TE$_{19,6}$	TEM$_{00}$	1.37	42.9	0.0001	
				0.8	30	0.1	
	124.3	TE$_{20,7}$	TEM$_{00}$	1.18	37.0	0.0001	
				0.85	29	10	
	127.6	TE$_{21,7}$	TEM$_{00}$	1.33	41.6	0.0001	
	140.1	TE$_{22,8}$	TEM$_{00}$	1.42 (1.7)	43.3 (42)	0.0001	
				1.2	68 (SDC)	0.0001	
				0.95	52 (SDC)	10	
	152.6	TE$_{23,9}$	TEM$_{00}$	1.44	44.2	0.0001	
	156.0	TE$_{24,9}$	TEM$_{00}$	1.01	36.1	0.0001	
	104	TE$_{18,7}$	TEM$_{00}$	0.98	46.5 (SDC)	0.5	
	140	TE$_{22,10}$	TEM$_{00}$	0.99	47 (SDC)	0.5	
JAEA[2)], TOSHIBA	136.8	TE$_{25.9}$	TEM$_{00}$	1.35	30.5	0.0005	2f-Gyrotron
Naka, Otawara				0.6	37 (SDC)	10	
[478,481]	170	TE$_{31.11}$	TEM$_{00}$	1.30	29	0.0005	
				0.55	24 (SDC)	50	
MIT, Cambridge [547-554]	107.1	TE$_{21,6}$	TEM$_{00}$	1.1	30	0.000003	3f-Gyrotron
	110.1	TE$_{22,6}$	TEM$_{00}$	1.4	37	0.000003	
	113.0	TE$_{23,6}$	TEM$_{00}$	1.1	30	0.000003	

SDC: Single-stage Depressed Collector;
[1)] formerly KfK, then FZK, [2)] formerly JAERI

Table VII: Step-tunable conventional cavity 1 MW gyrotron with broadband Quartz Brewster angle window at KIT (U_c = 82 kV, I_b= 45 A). Pulse duration up to 7 ms with Silicon Nitride (Kyocera SN-287) Brewster angle window. Two and three-frequency and multi-frequency GYCOM gyrotrons with matched plane BN or CVD-diamond windows. The 140 GHz TE$_{22,10}$-mode tube was also operated in 50-150 ms pulses with a BN Brewster window (11 frequencies at 0.8 MW between 104 and 143 GHz). Two-frequency JAEA/TOSHIBA and three-frequency MIT gyrotron.

The KIT 1 MW $TE_{22,6}$ gyrotron operated at frequencies between 114 and 166 GHz has been investigated with respect to fast-frequency tunability in the frequency range from 132.6 to 147.4 GHz [72]. For that purpose, the gyrotron has been equipped with a special hybrid-magnet system consisting of superconducting (sc) magnets in the cryostat and additional normalconducting (nc) copper magnets with a fast time constant. Special problems due to the magnetic coupling between the different magnets were investigated by calculation and experiment. Making use of these investigations different current regulation schemes for the nc magnets were implemented and tested experimentally. Finally a step-tuning operation between the modes from $TE_{20,6}$ to $TE_{24,6}$ in time steps of 1 s has been achieved. Currently, KIT is developing a corresponding, fully superconducting magnet in collaboration with Cryomagnetics, USA.

Institution	**Frequency [GHz]**	**Mode** cavity	output	**Power [MW]**	**Efficiency [%]**	**Pulse length [s]**
KIT[1], Karlsruhe	136.3	$TE_{26,14}$	TEM_{00}	1.02	23.5	0.001
[71,496-499,501-503]	138.7	$TE_{27.14}$	TEM_{00}	1.14	26.1	0.001
	140.8	$TE_{28,14}$	TEM_{00}	0.92	24.0	0.001
	142.2	$TE_{26,15}$	TEM_{00}	0.90	20.6	0.001
	144.4	$TE_{27,15}$	TEM_{00}	0.96	23.1	0.001
	146.7	$TE_{28.15}$	TEM_{00}	1.13	25.6	0.001
	149.0	$TE_{29,15}$	TEM_{00}	1.08	22.9	0.001
	151.1	$TE_{30,15}$	TEM_{00}	1.00	21.3	0.001
	152.4	$TE_{28,16}$	TEM_{00}	0.75	20.8	0.001
	154.6	$TE_{29,16}$	TEM_{00}	0.94	23.4	0.001
	156.9	$TE_{30,16}$	TEM_{00}	1.24	25.4	0.001
	159.2	$TE_{31,16}$	TEM_{00}	1.04	23.9	0.001
	160.7	$TE_{29,17}$	TEM_{00}	0.99	20.7	0.001
	162.8	$TE_{30,17}$	TEM_{00}	0.98	20.7	0.001
	165.1	$TE_{31,17}$	TEM_{00}	1.24	26.3	0.001
				1.24	41 (SDC)	0.001
	167.2	$TE_{32,17}$	TEM_{00}	1.22	25.6	0.001
EGYC[2] [527-530]	141.3	$TE_{28.16}$	TEM_{00}	1.8	26	0.001
	170.0	$TE_{34.19}$	TEM_{00}	2.2	30	0.001

SDC: Single-stage Depressed Collector;
[1] formerly KfK, then FZK,
[2] EGYC is a collaboration among CRPP, Switzerland; KIT, Germany; HELLAS, Greece; CNR, Italy; ENEA Italy

Table VIII: Step-tunable 1 MW and 2 MW gyrotrons with coaxial cavity (tapered and longitudinally corrugated inner rod) and broadband Silicon Nitride (Kyocera SN-287) Brewster window.

A specific feature of the coaxial gyrotron design is that it allows electron beam energy recovery and very fast frequency tuning by biasing the coaxial insert [536-539]. By biasing the inner rod of the KIT coaxial cavity gyrotron, such very fast (within ≈ 0.1 ms) frequency tuning has been demonstrated at a power level of 1 MW. In particular, step frequency tuning between the 165.1 GHz nominal mode and its azimuthal neighbors at 162.8 GHz and 167.2 GHz (see Table VIII) has been performed. In addition, operating in the nominal mode $TE_{31,17}$ a continuous frequency pulling within the bandwidth of up to 70 MHz has been performed [503].

Material	Type	Power (kW)	Frequency (GHz)	Pulse Length (s)	Institution
water-free fused silica	single-disk inertially cooled	200	60	5.0	UKAEA/Culham
boron nitride	single-disk water edge cooled	930	110	2.0	GYCOM-M
		350	110	10	GYCOM-M
		960	140	1.2	GYCOM-M
		550	140	3.0	GYCOM-M
		100	140	80	GYCOM-M
		1030	170	1.0	GYCOM-M
		500	170	5.0	GYCOM-M
		270	170	10	GYCOM-M
silicon nitride	single-disk gas face and water edge cooled	130	84	30.0	NIFS/CPI
		520	168	1.0	NIFS/TOSHIBA
sapphire	single-disk LN_2 edge cooled	530	118	5.0	CEA/CRPP/FZK/TED
		350	118	100	CEA/CRPP/FZK/TED
		285*	140	3.0	IAP/INFK
		500	140	0.5	KIT/IAP/IPF/IPP
		370	140	1.3	KIT/IAP/IPF/IPP
sapphire	single-disk LHe edge cooled	410	110	1.0	JAEA/TOSHIBA
		500	110	0.5	JAEA/GA
sapphire	double-disk FC75 face cooled	200	60	CW	CPI
		400	84	10.5	NIFS/CPI
		350	110	5.0	JAEA/TOSHIBA
		200	140	CW	CPI
		500	170	0.6	JAEA/TOSHIBA
sapphire	distributed water cooled	65**	110	0.3	GA/JAEA
		200*	110	0.7	GA/CPI
Au-doped silicon	single-disk CO_2 gas edge cooled	600	140	0.8	GYCOM-M
diamond	single-disk water edge cooled	600	70	2.3	CPI
		1.2	77	10	TOHOKU/TOSHIBA
		0.3	77	900	TOHOKU/TOSHIBA
		500	84	2.0	CPI
		300**	110	1.0	CPI/FOM
		50	110	CW	CPI/FOM
		450	110	2.0	GYCOM-M/GA
		1050	110	5.0	CPI/GA
		600	110	10	CPI/GA
		1500	110	4.0	JAEA/TOSHIBA
		1000	110	30	JAEA/TOSHIBA
		340	118	50	KIT/CEA/TED
		300	118	111	KIT/CEA/TED
		1000	140	12	KIT/CEA/CRPP/TED
		920	140	1800	KIT/CEA/CRPP/TED
		900	140	1800	CPI
		1000	170	570	GYCOM
		800	170	800	GYCOM
		1000	170	800	JAEA/TOSHIBA
		800	170	3600	JAEA/TOSHIBA

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

Tab. IX: Experimental parameters of high-power millimeter-wave vacuum windows [12,16,17,19,54,77-82,192,193,250-261,265,271,275,276,302-380,398-426 428-482,546,555-601].

Material	BeO p.c.	BN (CVD) p.c.	Si_3N_4 composite (SN-287)	Sapphire (Al_2O_3) s.c.	Silicon Au-doped s.c.	Diamond (PACVD) p.c.	Si C (6 H) p.c.
Thermal Conductivity k [W/mK]	260	55	59	40	150	2000	330
Ultimate Bending Strength σ_B[MPa]	140	80	800	410	1000	500	440
Poissons Number ν	0.3	0.25	0.28	0.22	0.1	0.1	0.18
Density ρ [g/cm³]	2.85	2.3	3.4	4.0	2.3	3.515	3.2
Specific Heat Capacity c_p [J/g K]	1.05	0.8	0.6	0.8	0.7	0.502	0.38
Young's Modulus E [GPa]	345	70	320	385	190	1050	700
Therm. Expans. Coeff. α [10^{-6}/K]	7.2	3	2.4	5.5	2.5	1.0	4.3
Permittivity (145 GHz) ε_r'	6.7	4.7	7.84	9.4	11.7	5.67	9.92
Loss Tangent (145 GHz) tanδ [10^{-5}]	70	115	30	20	0.35	2	7
Metallizing/Brazing Bakeout	o.k.	o.k.	o.k. 550°C	o.k. 550°C	o.k 550°C	o.k. 450°C	o.k. 550°C
Possible Size ∅ [mm]	150	145	300	270	127	120	
Cost	medium	medium	high	high	low	very high	medium
Failure Resistance R' $R' = k\sigma_B(1-\nu)/E\alpha$	10.3	15.7	44.5	6.0	284	858	40
RF-Power Capacity P_T $P_T = R'\rho\, c_P/((1+\varepsilon_r')\tan\delta)$	0.06	0.05	0.36	0.09	106	118	0.63
Radiation Sensitivity n(10^{20}-10^{21}n/m²) γ/X (0.75 Gy/s)				no no	no no	no no	

Tab. X: 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) [54,60,576,602-604].

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	1000	500
Poissons Number ν	0.22	0.1	0.1
Density ρ [g/cm³]	4.0	2.3	3.52
Specific Heat Capacity c_p [J/g K]	0.8	0.7	0.52
Young's Modulus E [GPa]	402 (405)	190	1050
Therm. Expans. Coeff. α [10^{-6}/K]	5.5	2.5	1.2
Permittivity (145 GHz) ε_r'	9.3	11.5	5.67
Loss Tangent (145 GHz) $\tan\delta$ [10^{-5}]	0.57 (0.2)	0.35	2
Metallizing/Brazing Bakeout	o.k. 550°C	o.k 550°C	o.k. 450°C
Possible Size ∅ [mm]	270	127	160
Cost	high	low	very high
Failure Resistance R' $R' = k\sigma_B (1-\nu)/E\alpha$	130 (2871)	2463	3571
RF-Power Capacity P_T $P_T = R'\rho\, c_P/((1+\varepsilon_r')\tan\delta)$	71 (4460)	907	490
Radiation Sensitivity n($0.3 \cdot 10^{21}$n/m²) γ/X (0.75 Gy/s)	no no	no no	no no

Tab. XI: 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) [576].

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 [52-56,60,576]. The features of beryllia, boron nitride, silicon nitride (Kyocera SN-287), sapphire, Au-doped silicon, CVD diamond and silicon carbide at room temperature and of sapphire, Au-doped silicon and CVD diamond at cryo-temperatures are summarized in Tables X and XI, where

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

and

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

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

The comparison of R' and P_T for the four materials BeO, BN, Si_3N_4 and sapphire clearly shows that there is no chance to use these dielectrics as an edge-cooled, single-disk CW window at room temperatures. Experiments at CPI in the US and at NIFS and JAEA in Japan confirmed, that even a double disk FC75-face-cooled sapphire window has a CW-power limit around
0.3-0.4 MW. Nevertheless these materials are widely used at lower frequencies and pulsed operation.

At LN_2-temperature 77 K (LNe-temperature 30 K) sapphire has a thermal conductivity of 900 (20000) W/mK and a loss tangent of $5.7 \cdot 10^{-6}$ ($2 \cdot 10^{-6}$) leading to R' = 130 (2870) and P_T = 70 (4460). The LN_2-edge-cooled sapphire window of the 118 GHz TED gyrotron (0.5 MW, 210 s) [366-376] operates close to the allowable lower limits of R' and P_T. However, the mecha-nical features and the required cooling auxillaries make such cryo-windows very complicated. Au-doped silicon at temperatures somewhat lower than 0°C could avoid a thermal runaway and transmit 1 MW, CW but this material is too brittle and tends to mechanical cracking [564].

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 XII [52-56,60,576]. The diamond options 2 and 3 being water cooled, are preferred for their simplicity, in particular for use as 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 XII: Options for 1 MW, CW, 170 GHz gyrotron windows [52-56,60,576].

7 Harmonic and Very High Frequency Gyrotron Oscillators

Institution	Frequency [GHz]	Mode	Power [kW]	Efficiency [%]	Pulse length [ms]
CPI[1)], Palo Alto [605]	250	$TE_{11,1}/TE_{11,2}$	10	3.4	0.1
IAP, N. Novgorod [88,89,606]	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 [607,608]	209	TE_{92}	15	3.5	0.001
	241	$TE_{11,2}$	25	6.5	0.001
	302	TE_{34}	4	1.5	0.0015
	339	$TE_{10,2}$	4	3	0.0015
	363	$TE_{11,2}$	7	2.5	0.0015
	417	$TE_{10,3}$	15	6	0.0015
	457	$TE_{15,2}$	7	2	0.0015
	467	$TE_{12,3}$	22	3.5	0.0015
	503	$TE_{17,2}$	10	5.5	0.0015
UESTC, Chengdu [609]	423	TE_{26}	4.4	2.8	0.004
UNIVERSITY, Fukui [96-107,610-622]	350.3	TE_{65}	52	8.3	0.004
	384[*)]	TE_{26}	3	3.7	1
	392.6	TE_{85}	60	9.6	0.004
	402[*)]	TE_{55}	2	3	1
	576[*)]	TE_{26}	1	2.5	0.5
	874[*)]	TE_{19}	0.6	2.0	0.5

[1)] Communications & Power Industries; formerly VARIAN [*)] In collaboration with TOSHIBA, Ottawara

Table XIII a: Capabilities and performance parameters of mm- and submillimeter-wave gyrotrons operating at the second harmonic of the electron cyclotron frequency, with output power ≥ 1 kW.

Institution	Frequency [GHz]	Mode	Harmonic No. s	Power [kW]	Efficiency [%]	Pulse length [ms]
UNIVERSITY, Fukui	84.9	TE_{31}	3	2.5	6.3	1
IAP, N. Novgorod	89.3	TE_{31}	3	1.7	3.3	1
[623-628]	112.7	TE_{41}	4	0.47	1	1
	138.0	TE_{51}	5	0.1	0.2	1
IAP, N.Novgorod [94,95,629]	550	TE_{24}	2	0.6	2.2	0.01
	680	TE_{25}	2	1.8	3.5	0.01
	870	TE_{36}	3	0.3	0.9	0.01
	1000	TE_{37}	3	0.4	0.7	0.01

Table XIII b: Operation results of high harmonic gyrotrons with axis-encircling electron beam (LOG) and permanent magnet (Nd Fe B) at University of Fukui and pulsed magnet at IAP (THz gyrotron).

Institution	Frequency [GHz]	Mode	Power [MW]	Efficiency [%]	Pulse length [μs]	
IAP, Nizhny Novgorod [88-94]	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	
	1002	$TE_{6.8}$	0.0018	2.4	40	
	1024	$TE_{17,4}$	0.005	6.1	40	
	1300	$TE_{24,4}$	0.0005	0.6	40	
MIT, Cambridge [63,315,541,547-554, 630-640]	107.1	$TE_{21,6}$	0.94	24	3	
	110	$TE_{22,6}$	1.67	42	3	
		TEM_{00}	1.5	48 (SDC)	3	
	113.2	$TE_{23,6}$	1.18	30	3	
	140	TE_{04}	0.025	7.4	3	PBG resonator BW = 35%
	140	$TE_{15,2}$	1.33	40	3	
	148	$TE_{16,2}$	1.3	39	3	
	166.6	$TE_{27,8}$	1.50	34	3	
	170.0	$TE_{28,8}$	1.50	35	3	
	173.4	$TE_{29,8}$	0.72	29	3	
	188	$TE_{18,3}$	0.6		3	
	225	$TE_{23,3}$	0.37		3	
	231	$TE_{38.5}$	1.2	20	3	
	236	$TE_{21,4}$	0.4		3	
	267	$TE_{28,4}$	0.2		3	
	280	$TE_{25,13}$	0.78	17	3	
	287	$TE_{22,5}$	0.537	19	3	
	320	$TE_{29,5}$	0.4	20	3	
	327	$TE_{27,6}$	0.375	13	3	
UESTC, Chengdu [641]	221	TE_{03}	0.02	8.5	4	
	226	TE_{23}	0.02	14.0	4	
UNIVERSITY, Fukui [611,612]	278	TE_{33}	0.001	5	1000	
	290	TE_{62}	0.001	4	1000	
	314	TE_{43}	0.001	4	1000	

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

Operating at the fundamental, the 2nd harmonic or the 3rd harmonic of the electron cyclotron frequency enables the gyrotron to act as a medium power (several 1-100 W) step tunable, mm- and sub-mm wave source in the frequency range from 38 GHz (fundamental) to 1.014 THz ($TE_{4,12}$ mode, 2nd harmonic) [96-135,606-649].

A low power (30 W) two-cavity gyrotron with frequency multiplication achieved at IAP an efficiency of 0.43%. The first cavity operated in the TE_{01} mode near the fundamental cyclotron frequency at 95 GHz, the output cavity operated at the 3rd harmonic 285 GHz in the TE_{03} mode [650-654]. Simultaneous generation at the 2nd (37.5 GHz) and 4th (75 GHz) harmonic (140 W at 60 kV and 6A) has been obtained from a self-excited gyromultiplier with single, sectioned cavity [655,656].

Institution	Frequency [GHz]	Mode	Voltage [kV]	Current [A]	Power [MW]	Efficiency [%]
MIT, Cambridge [631]	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 XV: Step tuning of MIT gyrotron oscillator (with large MIG [631]) operating at the fundamental electron cyclotron resonance frequency (pulse length 1.5 μs).

Institution	Frequency [GHz]	Mode	Voltage [kV]	Current [A]	Power [MW]	Efficiency [%]
MIT, Cambridge [631]	249.6	$TE_{24,11}$	71	41	0.39	14
	257.5	$TE_{23,12}$	87	41	0.33	9
	267.5	$TE_{25,12}$	85	33	0.35	12
	277.2	$TE_{27,12}$	78	42	0.45	14
	280.1	$TE_{25,13}$	92	51	0.78	17
	285.2	$TE_{26,13}$	93	41	0.42	11
	282.8	$TE_{23,14}$	94	39	0.54	15
	287.9	$TE_{24,14}$	94	51	0.64	14
	292.9	$TE_{25,14}$	95	41	0.72	18
	302.7	$TE_{27,14}$	96	43	0.27	7

Table XVI: Step tuning of MIT gyrotron oscillator (with small MIG [631]) operating at the fundamental electron cyclotron resonance frequency (pulse length 1.5 μs).

8 Gyrotrons for Technological Applications

Institution	Frequency [GHz]	Mode cavity	Mode output	Power [kW]	Efficiency [%]	Voltage [kV]	Magnet
CPI[1], Palo Alto [11,16,605]	28	TE_{02}	TE_{02}	15	38	40	roomtemp.
	28 ($2\Omega_c$)	TE_{02}	TE_{02}	10.8	33.6	30	roomtemp.
	60	TE_{02}	TE_{02}	30	38	40	cryo. mag.
CPI, NIFS [48-50,262-265] Palo Alto, Toki	84	$TE_{15,3}$	TEM_{00}	50	14	80	cryo. mag.
GYCOM/IAP Nizhny Novgorod, [1,12,65,78,79,142-146, 149,152-154,156-161, 268,427,428,606,657-668]	13	TE_{01}	TE_{01}	0.3	20	25	roomtemp.
	15	TE_{01}	TE_{01}	4	50	15	roomtemp.
	24.1 ($2\Omega_c$)	TE_{11}	TE_{11}	3.5	23	12	roomtemp.
	24.1 ($2\Omega_c$)	TE_{-21}	TE_{11}	3.4	23	15	PM, 116kg
	24.1	TE_{32}	TE_{32}	36	50	33	roomtemp.
	24.1 ($2\Omega_c$)	TE_{12}	TE_{12}	13	50	25	roomtemp.
				28	32	25	roomtemp.
				6.5	60 (SDC)	17.5	roomtemp.
	28/30 ($2\Omega_c$)	TE_{02}	TE_{02}	10	42	26	roomtemp.
				30	35	26	roomtemp.
	28.25 ($2\Omega_c$)	TE_{12}	TE_{12}	12	20	25	PM, 68 kg[2]
	31.8-34.8	TE_{11}	TE_{11}	1.2	40	12	mech. tun.
	35.5-37.5	TE_{01}	TE_{01}	0.5	15.3	16	mech. tun.
	35.15	TE_{02}	TE_{02}	9.7	43	25	cryo. mag.
	35	TE_{02}	TEM_{00}	10-40	30-40	25-30	cryo. mag.
	37.5	TE_{62}	TEM_{00}	20	35	30	cryo. mag.
	68-72	TE_{13}	TE_{13}	1.4	22	17.5	mech. tun.
	83	TE_{93}	TEM_{00}	10-40	30-40	25-30	cryo. mag.
	150	TE_{03}	TE_{03}	22	30	40	cryo. mag.
	157 ($2\Omega_c$)	TE_{03}	TE_{03}	2.4	9.5	18	cryo. mag.
	191.5 ($2\Omega_c$)			0.55	6.2	22	cryo. mag.
	250 ($2\Omega_c$)	TE_{02}	TE_{02}	4.3	18	20	cryo. mag.
	250 ($2\Omega_c$)	TE_{65}	TE_{65}	1	5	20	cryo. mag.
	326 ($2\Omega_c$)	TE_{23}	TE_{23}	1.5	6	20	cryo. mag.
MICRAMICS, San Jose [669]	24.1 ($2\Omega_c$)	TE_{22}	TEM_{mixed}	5	25	23	roomtemp.
			TE_{22}	10	25	23	roomtemp.
MITSUBISHI, Amagasaki [155,670-672]	28 ($2\Omega_c$)	TE_{02}	TE_{02}	10	38.7	21	PM, 600 kg[2] tapered B
UESTC, Chengdu [673]	37.5	TE_{13}	TE_{13}	57 (0.4 average)	9	50.5	roomtemp.
UNIV. Fukui, IAP Nizhny Novgorod/ GYCOM [148,674-680]	300	$TE_{22,8}$	TEM_{00}	2.3	16.4	14	cryo. mag.

[1] Communications & Power Industries, formerly VARIAN [2] PM: permanent magnet

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

IAP Nizhny Novgorod and GYCOM have developed a dual-frequency materials processing system employing a 15 kW, 28 GHz gyrotron and a 2.5 kW, 24.1 GHz tuneable gyro-BWO (see Table XXVIII) [149,152,153]. This system has been installed at the University of Fukui, Japan.

9 Relativistic Gyrotrons

Institution	Frequency [GHz]	Mode	Voltage [MV]	Current [kA]	Power [MW]	Efficiency [%]	Type
IAP, Nizhny Novgorod [681-688]	9.23	TE_{01}	0.27 (0.28)	0.12 (0.06)	10 (7.0)	32 (55)	
	20	TM_{01}	0.5	0.7	40	11.4	
	30	TE_{53}	0.3	0.08	12	50	
	30 (35)	$TE_{5,3}$ ($TE_{6,3}$)	0.38	0.11	20	50	
	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	10	TE_{13}	0.3	1.0	60	15	plasma-filled slotted cavity
[682,689-691]	40	TE_{13}	0.4	1.3	25	5	slotted cavity
KIPT, Kharkov [692]	12	TE_{13}	0.12	8.0	60	6.3	plasma filled slotted cavity
UNIV. Michigan [693-699]	2.88	TE_{01}^{r}	0.8	2 (7)	20	1.3 (0.4)	small orbit
			0.8	0.35 (1.2)	6	2.1 (0.06)	large orbit
	2.15	TE_{10}^{r}	0.8	0.35 (1.2)	14	5.0 (0.15)	large orbit
	2.5	TE_{11}^{c} (coax.)	0.8	0.8 (4.0)	90	14 (2.8)	large orbit, slotted cavity
					40		unslotted cavity
					20		unsl. noncoax. cavity
	10	TE_{11}	0.4	0.025	0.6	6	
NRL, Washington D.C. [700-703]	8.35-13	4-5 modes	3.3	80	1000	0.4	superradiant
	35	TE_{62}	0.78	1.6 (3.5)	100	8 (4) *)	
			1.15	2.5	275	10	
	35	TE_{13}	0.9	0.65	35	6	slotted cavity
Tomsk Polytech. Inst. [704]	3.1		0.75	8.0 (30)	1800	8	also vircator interaction
UNIV. Niigata [705]	18.2	TE_{01}	0.08	0.5	0.2	0.55	
UNIV. Strathclyde [706-711]	23	TE_{12}	0.1	0.5	5	10%	
	100		0.2	0.22	6.3	14	

r: rectangular waveguide
*) operation from 28 to 49 GHz by magnetically tuning through a family of TE_{m2} modes, with the azimuthal index m ranging from 4 to 10

Table XVIII: Present development status of relativistic gyrotron oscillators.

Institution	Frequency [GHz]	Mode	Harmonic No. s	Voltage [MV]	Current [kA]	Power [MW]	Efficiency [%]
IAP, Nizhny Novgorod [215,653,712-720]	21.6	TE_{11}	1	0.3	0.03 (3)	1.5	16.7 (0.17)
	35.7	TE_{21}	2	0.3	0.03 (3)	1.5	16.7 (0.17)
	49.1	TE_{31}	3	0.3	0.03 (3)	0.5	6.7 (0.07)
	62.4	TE_{41}	4	0.3	0.03 (3)	0.2	2.2 (0.02)
	74.9	TE_{51}	5	0.3	0.03 (3)	0.12	1.3 (0.013)
	115.2	TE_{32}	3	0.25	0.008	0.1	5.0
	130.3	TE_{42}	4	0.25	0.008	0.1	5.0
	223	TE_{25}	2	0.25	0.003	0.045	6.0
	369	TE_{35}	3	0.25	0.003	0.019	2.5
	371	TE_{38}	3	0.25	0.002	0.010	2.0
	414	TE_{39}	3	0.25	0.002	0.008	1.7
	469	TE_{35}	3	0.25	0.003	0.020	2.5

Table XIX: Relativistic large orbit harmonic pulse gyrotrons with axis-encircling electron beam. The 21.6, 35.7, 49.1, 62.4 and 74.9 GHz experiments used an explosive-emission cathode with kicker (τ = 10 ns) and the 115, 130, 223, 369, 371, 414 and 469 GHz experiments employed a quasi-Pierce type thermionic gun with kicker (τ = 10 μs, 1 Hz).

10 Quasi-Optical Gyrotrons

Institution	Frequency [GHz]	Mode resonator	Power [kW]	Efficiency [%]	Pulse length [ms]	Type
ABB, Baden [192,247]	92	TEM_{00q}	90	10	10	
CRPP, Lausanne [61,62,192,721]	90.8	TEM_{00q}	150	15	5	
	100	TEM_{00q}	90	15	15	
	200 ($2\Omega_c$)	TEM_{00q}	8	3.5	15	
IAP, Nizhny Novgorod [722]	100	TE_{061}	260	6.5	0.04	echelette cavity
MIT, Cambridge [723,724]	136	$HE^{()}_{061}$	83	18	0.003	confocal
	114.3	$HE^{()}_{051}$	75	16	0.003	slot-cavity
Moscow-State UNIV. [725]	35	TEM_{00q}	1	15	CW	
	95	TEM_{00q}	1	15	CW	
NRL, Washington D.C. [545,726,727]	110	TEM_{00q}	80	8	0.013	
	115	TEM_{00q}	600	9	0.013	
			431	12.7 (SDC)	0.013	
			197	16.1 (SDC)	0.013	
	120	TEM_{00q}	600	9	0.013	
			200	12	0.013	
TOSHIBA, Otawara [294]	112	TEM_{00q}	100	12	5	
	120	TEM_{00q}	26	10 (DEB)	3	

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

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

11 Cyclotron Autoresonance Masers (CARMs)

Institution	Frequency [GHz]	Mode	Power [MW]	Efficiency [%]	Gain [dB]	B-Field [T]	Voltage [MV]	Current [kA]	Type
IAP	31.5-34.5	TE_{11}^{*}/TE_{21} ($2\Omega_c$)	3.4	17 (0.21)	-	1.05-1.2	0.40	0.05 (4)	CARM-BWO
IAP	35.7	TE_{51}	30	10	-	1.12	0.4	0.6	oscillator
IAP	36.5	TE_{11}	9	18 (0.45)	-	1.15	0.4	0.6	oscillator
IAP, IHCE	37.5	TE_{11}	10	4	30	0.5	0.5	0.5	amplifier
IAP, U. Strath., HERC	37.5	TE_{21}	0.2	0.5 (0.25)			0.15	0.25 (0.5)	superradiance
IAP	38	TE_{11}^{*}/TE_{21} ($2\Omega_c$)	13	26 (0.65)	-	1.24	0.5	0.1 (4)	CARM-gyrotron
	40	TE_{11}	6	22 (0.44)	-		0.46	0.06 (0.3)	oscillator
IAP, IHCE, JINR	50	TE_{11}	30	10	-	0.7	1.0	0.3	oscillator
IAP	66.7	TE_{21}	15	3	-	0.6	0.5	1.0	oscillator
IAP, IHCE, JINR	68	TE_{11}	50	8	-	1.0	1.2	0.5	oscillator
IAP	69.8	TE_{11}	6	4	-	0.6	0.35	0.4	oscillator
IAP [712,713,728-737]	125	TE_{41}	10	2	-	0.9	0.5	1.0	oscillator
LLNL Livermore [738]	220	TE_{11}	50	2.5	-	3.0	2.0	1.0	oscillator
MIT Cambridge [203,739,740]	27.8	TE_{11}	1.9	5.3	-	0.6	0.45	0.080	oscillator
	30	TE_{11}	0.1	3	-	0.64	0.3	0.012	oscillator
	32	TE_{11}	0.11	2.3	-	0.63	0.32	0.015	oscillator
	35	TE_{11}	12	6.3 (0.04)	30	0.7	1.5	0.13 (20)	amplifier
UNIV. Michigan [741,742]	15	TE_{11}	7	1.5	-	0.45	0.4	1.2	oscillator
UNIV. Strathclyde [743-745]	13	TE_{11}			-	0.3	0.4	0.04	oscillator
	14.3 ($2\Omega_c$)	TE_{21}	0.18	4 (0.4)	-	0.2	0.3	0.015 (0.15)	oscillator

[*] output

HERC Moscow, IAP Nizhny Novgorod, IHCE Tomsk, JINR Dubna

Table XXI: State-of-the-art of fast-wave CARM experiments (short pulse).

Institution	Frequency [GHz]	Mode	Power [MW]	Efficiency [%]	Gain [dB]	B-Field [T]	Voltage [MV]	Current [kA]	Type
UNIV. Lomonosov, Moscow [204]	9.5	TM_{01}	35	3.5	-	1.15	0.4	2.5	oscillator corr.w.g.
Tomsk Polytechn. Inst. [205]	25		20	0.2	-	0.64	0.9	14	oscillator diel.w.g.
UNIV. Niigata, NIFS, UNIV. Maryland [206]	19.5	TM_{01}	0.2	3.8	-	0.9	0.035	0.15	oscillator corr.w.g.
UNIV. Yale, NRL, Washington D.C. [207]	6.2	TE_{01}	0.02	10	53	0.2	0.05	0.005	amplifier diel.w.g.

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

12 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 [%]	Type
CPI[1], Palo Alto [16,189]	10 ($2\Omega_c$)	TE_{01}	3	20	8.2	10	0.2	
	28	$TE_{01/02}$	2	76	9	30	0.2	
	35			65		30	0.2	
CPI, Litton, NRL, U.M. [171,315,746-753]	93.8	TE_{01}	4	118	29.5	24.7	0.64	SN1
			5	130	33	39.5	0.75	SN2
GYCOM-M(TORIY), Moscow [754,755]	35.2	TE_{02}	2	750 (5av.)	24	20	0.6	max. power
			2	350	32	19	0.9	max. efficiency
	35.0	TE_{01}	4	160	48	42	1.4	
			3	250 (1.2av.)	35	40	1.4	
IAP Nizhny Novgorod [756-768]	9.25	TE_{01}	2	4	50	22	1.0	
			3	16	45	22	1.0	
	15.2	TE_{01}	3	50	50	30	0.5	
	15.8	TE_{02}	3	160	40	30	0.5	max. efficiency
	32.4 ($2\Omega_c$)	TE_{02}	3	300	22	22	0.1	PM, 350 kg
	34	TE_{01}	4	280	32	34	0.53	
	35.12 ($2\Omega_c$)	TE_{02}	2	258	18	17	0.3	tapered B-field
	35	TE_{02}	2	300	22		0.3	2-cav. Gyrotron
				230	30		0.3	2-cav. Gyrotron
	93.2	TE_{01}	4	65	26	35	0.3	max. power
			4	57	34	40	0.3	max. efficiency
	93.5	TE_{02}	2	140	18	18	0.35	
			2	207	30	21	0.2	shaped B
	93.2	TE_{02}	3	340	24.5	23	0.3	shaped B
IECAS, Beijing [769,770]	35 ($2\Omega_c$)	TE_{02}	3	212	16	24	0.44	
Kwangwoon Univ., Seoul [771]	27.85	TE_{01}	5	150	26	50	0.1	
NRL, Washington D.C. [168-171,189,545, 772-783]	4.5	TE_{10}	3	54	30	30	0.4	
	34.95	TE_{01}	2	210	37	24	0.35	
	34.9	TE_{01}	3	225	31	30	0.82	
	34.9	TE_{01}	4	208	30	53	0.5	
	85	TE_{13}	2	50		20		
	85.5	TEM_{00}	2	82	19	18		QOGK
				82	30 (SDC)	18		QOGK
	93.4	TE_{01}	4	60	25	27	0.69	max. BW
				84	34	42	0.37	max. power
			5	72	27	48	0.44	max. pow.xBW
UESTC, Chengdu [784]	34	TE_{01}	4	300 (5 av.)	30	36	1.0	

- Weakly Relativistic CW Gyroklystrons

Institution	Frequency [GHz]	Mode	No. of cavities	Power [kW]	Efficiency [%]	Gain [dB]	BW [%]	Type
CPI, Litton, NRL, U.M. [168-172,253,748-753]	93.8	TE_{01}	4	10.1	33.5	32	0.45	(92 kW, 11% duty)
	94.2	TE_{01}	5	10.2	31	33	0.75	(102 kW,10% duty)
IAP Nizhny Novgorod [758]	9.17	TE_{11}	2	0.7	70	22	0.3	
IAP/ISTOK Moscow [759,762]	91.6	TE_{01}	4	2.5	25	31	0.36	

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

[1] Communications & Power Industries, formerly VARIAN

Table XXIII: Weakly relativistic gyroklystron experimental results.

Institution	Frequency [GHz]	Mode output	No. of cavities	Power [MW]	Efficiency [%]	Gain [dB]	BW [%]	Type
IAP, Nizhny Novgorod	30	$TE_{5,3}$	2 ($TE_{5,2}/TE_{5,3}$)	10	25	27	0.14	triode gun
[785-789]		$TE_{3,2}$	3 ($TE_{5,1}/TE_{5,2}/TE_{5,3}$)	6.5	25	30		
UNIV. Maryland	8.57	TE_{01}	3	75	32	30	0.2	coaxial
[162-166,790-802]	9.875	TE_{01}	2	24	30	33	0.2	
	9.87	TE_{01}	3	27	32	36	0.2	max. power
			3	16	37	33	0.2	max. efficiency
			3	20	28	50	0.2	max. gain
	17.14 ($2\Omega_C$)	TE_{02}	3	27	13	25	0.1	coaxial
			4	18.5	7.0	23.3	0.35	coaxial
	19.76 ($2\Omega_C$)	TE_{02}	2	32	29	27	0.1	
	29.57 ($3\Omega_C$)	TE_{03}	2	1.8	2.0	14	0.1	

Table XXIV: Relativistic pulse gyroklystron experimental results.

Institution	Frequency [GHz]	Mode	Power [kW]	Efficiency [%]	Gain [dB]	Bandwidth [%]	Type
BVERI, Beijing [803,804]	35.3	TE_{01}	86	21.3	33	6	SiC loading
CPI[1], Palo Alto	5.18	TE_{11}	120	26	20	7.3	MIG
[16,172,189,315,753,	5.2	TE_{11}	64	14	17.5	7.3	Pierce-helix gun
805-808]	93.7	TE_{11}	28	7.8	31	2	Pierce-helix gun
	95	TE_{01}	1.5 (0.6 av.)	4.2	42	7.7	
IAP, Nizhny Novgorod [809-816]	36.3	TE_{-21}/TE_{+11}	180	27	27	10	cusp gun with axis-encircl. beam shortpulse 3 µs
			120	23	20	6	longpulse 110 µs
	30.5	TE_{-21}/TE_{+11}	3	6.5	33	5	CW operation
MIT, Cambridge [817-826]	140	$HE^{()}_{061}$	30	12	29	1.6	quasi-optical at 1 kW 400 ps modulaton pulse
NRL, Washington D.C.	32.5	TE_{10}	6.3	10	16.7	33	1-stage tapered
[189,827-833]	35.5	TE_{10}	8	16	25	20	2-stage tapered
	32.3	TE_{10}	50	28	25	11	folded waveguide axis-encircl. beam
	34.0	TE_{01}	137	17	47	3.3	2-stage output
	35.6	TE_{11}	70	17	60	17	2-stage output
UC Los Angeles/	9.3	TE_{10}	55	11	27	11	diel. coat. waveg.
Davis [834-846]	10.4 ($3\Omega_C$)	TE_{31}	6	5	11	3	axis-encirl. beam
	15.7 ($2\Omega_C$)	TE_{21}	207	12.9	16	2.1	slotted waveg.
	16.2 ($8\Omega_C$)	TE_{81}	0.5	1.3	10	4.3	axis-encircl. beam
	92	TE_{01}	140	22	60	2.2	heavily loaded + short copper stage
NTHU, Hsinchu	35.8	TE_{11}	18.4	18.6	18	10	
[209-211,847-853]	35.8	TE_{11}	27	16	35	7.5	2-stage severed
	34.2	TE_{11}	62	21	33	12	2-stage lossy (short)
	33.6	TE_{11}	93	26.5	70	8.6	2-stage lossy (long)
UESTC, Chengdu [854]	34	TE_{01}	160	22.8	40	5	lossy interaction circuit
UNIV. Tel Aviv [855]	7.3	TE_{10}	0.8	12	26		3-stage output

[1])Communications & Power Industries, formerly VARIAN

Table XXV: Present development status of weakly relativistic gyro-TWTs (short pulse).

Institution	**Frequency [GHz]**	**Mode**	**Power [MW]**	**Efficiency [%]**	**Gain [dB]**	**Bandwidth [%]**	**Type**
IAP, Nizhny Novgorod UNIV. Strathclyde [212,809-811,856-860]	9.4 ($2\Omega_C$)	TE_{-21}/TE_{+11}	1.1	29	37	21	helical waveguide with Δm=3 perturb. Axis encircl. E-beam
	36.5 ($2\Omega_C$)	TE_{-21}/TE_{+11}	3.0	27	33	20(ΔB)	see above
MIT, Cambridge [861]	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. *) [862,863]	35	TE_{11}	20	11	30		explosive-emission gun, bifilar helical wiggler
UNIV. Strathclyde [864-869]	9.4 ($2\Omega_C$)	TE_{-21}/TE_{+11}	0.22	20	24	21	thermionic MIG, superradiance
			1.3	27	47	3	cold cathode cusp gun

*) This gyro-TWT operated near the "grazing intersection" in the dispersion diagram could also have been considered a CARM amplifier with frequency 4.4 times the relativistic cyclotron frequency.

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

- Weakly Relativistic Pulse Gyrotwystrons

Institution	Frequency [GHz]	Mode cavity	Mode TW section	Power [kW]	Efficiency [%]	Gain [dB]	BW [%]
CPI[1], Palo Alto [169,172,253,753]	94	TE_{01} (4 cav.)	TE_{01}	59 (5.9 av.)	14.9	35	1.6
NRL, Washington D.C. [870]	4.5	TE_{10}	TE_{10}	73	22.5	37	1.5
	31.5	TE_{42} ($2\Omega_c$)	TE_{42}	160	25	30	1.3
	93.5	TE_{01} (3 cav.)	TE_{01}	48	17.5	30	2.0
IAP, N.Novgorod, NRL Washington D.C. [871,872]	9.2	TE_{01} (2 cav.)	TE_{01}	4.8	14	20	0.9
				4.4	27.5	18	1.6

[1]Communications & Power Industries, formerly VARIAN

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

Institution	Frequency [GHz]	Mode cavity	Mode TW section	Power [kW]	Efficiency [%]	Gain [dB]	BW [%]
IECAS [873-880]	33.1	TE_{01}/coupled cavity ($2\Omega_c$) TE_{02}/TE_{03}	$TE_{03}(\Omega_c)$	75	7.1	25	1.1
Seoul National UNIV. [881]	33.9	TE_{10}	$TE_{10}(3\Omega_c)$	10^{-4}	$2 \cdot 10^{-3}$	LO-gyro-TWT	3.8
UNIV. Maryland. [214,882-887]	31.8	TE_{22}	$TE_{42}(2\Omega_c)$	100	20	30	1.3
	33.7	TE_{02}	$TE_{03}(2\Omega_c)$	430	35	30	0.3
	34.6	TE_{02}	$TE_{03}(2\Omega_c)$	180	32	30 phase-locked oscillator	3.0
	32.5	TE_{02}	$TE_{03}(2\Omega_c)$	200	12	36 gyro-TWT	3.0
	35	TE_{02}/TE_{03} ($2\Omega_c$) buncher	TE_{04} ($2\Omega_c$)	110	32	53 gyro-TWT	3.0
	33.75	Gyrotriotron		126	12	27	3.2

TWT input stage (s_1=1) TE_{02} / 4-unit clustered cavities (s_2=2) TE_{03} / TWT output stage (s_3 = 2) TE_{04}

- Relativistic Pulse Gyrotwystrons

Institution	Frequency [GHz]	Mode cavity	Mode TW section	Power [MW]	Efficiency [%]	Gain [dB]	BW [%]
UNIV. Maryland [888]	9.878	TE_{01}	TE_{01}	21.6	21	25.5	
	19.76	TE_{01} (9.88GHz)	$TE_{02}(2\Omega_c)$	12	11	21	

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

- Weakly Relativistic Pulse Gyro-BWOs

Institution	Frequency [GHz]	Mode	Power [kW]	Efficiency [%]	Bandwidth [%]	Type
UNIV. Strathclyde IAP N. Novgorod [889-892]	8.6	TE_{+21}/TE_{-11}	58	16.5	17	quasi-Pierce gun with kicker
IAP, N. Novgorod KIT[1)], Karlsruhe [149,665,666,811-816, 893,894]	24.7	TE_{+21}/TE_{-11}	7	15 23 (SDC)	5	MIG CW operation
IAP, Nizhny Novgorod [810]	35-38	TE_{+21}/TE_{-11}	34	7	15	quasi-Pierce gun with kicker
	35	TE_{+21}/TE_{-11}	10	5	10	cusp gun with thermal cathode
IECAS, BVERI, Beijing [895,896]	17.2	TE_{01}	48	10.5 21(SDC)	5	TE_{10}^{r} output
MIT, Cambridge, LLNL, Livermore [897]	140	TE_{12}^{c}	2	2	9	
NRL, Washington D.C. [898]	27.8	TE_{10}^{r}	2	9	3	electr. tuning
	29.2	TE_{10}^{r}	6	15	13	magn. tuning
NTHU, Hsinchu [899-907]	33.5	TE_{11}^{c}	20-67	6.5-21.7	5	injection locked
			115	23	8.5	free running
			149	30	4	electr. + magn. tuning
			154	39	1	injection locked
			164	41	1	inverse injec. locked
		TE_{01}^{c}	123	24.5	15.8	sliced circuit
		TE_{02}^{c}	2.8	22.6	9.5	sliced circuit
UNIV. Strathclyde [908-910]	96	TE_{+21}/TE_{-11}	5	8	10	
UNIV. Utah [911]	10	TE_{10}^{r}	0.72	10	8	

r = rectangular waveguide; c = circular waveguide, [1)]formerly KfK, then FZK

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

Institution	Frequency [GHz]	Mode	Power [MW]	Efficiency [%]	BW [%]	Voltage [MV]	Current [kA]	Type
IAP, N. Novgorod [912,913]	10	TM_{11}	200	22		0.45	2	Cherenkov with cycl. mode selection
	35(2Ωc)	TE_{-21}/TE_{+11}	1.15	10 axis	15(ΔB) encirl.	0.35 e-beam	0.032	hel. w.g. with Δm=3 perturb.
UNIV. Kanazawa [914,915]	9-13	TE_{10}^{r}	1	0.75 (0.02)	1	0.45	0.3(10)	
UNIV. Michigan [916,917]	4-6	TE_{11}	55(30)	8(4.3)	1	0.7	1	
	5-6(2Ωc)	TE_{11}	1	0.15	4			
USAF Phillips Lab.	4.2	TE_{21}	4	1	1	0.4	1	
Aberdeen [918,919]	4.4	TE_{01}	0.15	0.04	1	0.4	1	

r = rectangular waveguide

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

Institution	Frequency [GHz]	Mode	Output Mode	Power [kW]	Efficiency [%]	Pulse length [ms]	Type
UC Davis [920]	34.1 ($2\Omega_c$)	TE_{11}^c	4x TE_{10}^r	88	36	0.02	cusp gun
UNIV. Tohoku, Sendai [921-929]	10.0	TE_{11}^r	TE_{11}^r	10	36	0.02	
	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	35 (75 electr.)		
				6.9	44(SDC) (92 electr.)		
	100 ($10\Omega_c$)	$TE_{11,1}^c$	TE_{01}^c	0.32	1.7 (5 electr.)		
	10	TE_{21}^c	TE_{21}^c	1.5	25		auto-res.

r = rectangular waveguide; c = circular waveguide, SDC = Single-stage depressed collector

Table XXIX: Experimental results of peniotrons.

Institution	Frequency [GHz]	Mode	Power [kW]	Efficiency [%]	Pulse length [ms]
UNIV. Tohoku, Sendai	69.85 ($3\Omega_c$)	TE_{02}	8	6.75	0.2
Toshiba, Otawara	140 ($3\Omega_c$)	TE_{03}	8	1	1
UNIV. Fukui [930]					

Table XXX: Experimental results of gyropeniotrons.

Institution	Frequency [GHz]	No. of Cavities	Voltage [MW]	Current [A]	Power [MW]	Efficiency [%]	Gain [dB]	Pulse length [µs]
BINP, Novosibirsk	0.915	3	0.3	12	2.6	73	30	30
[217,218,931-933]	7.01 ($2\Omega_c$)	5	0.427	230	55	56	72	1.1
NRL, Washington D.C.	11.424 ($2\Omega_c$)	7	0.48	210	25	25	59	0.2
[934-939]					12	12	59	1.2
NRL, Yale UNIV. /	34.3 ($3\Omega_c$)	7	0.455	187	17	19.5	47	0.1
Omega-P [939-943]					26	27	57	0.0005

BINP: Budker Institute of Nuclear Physics

Table XXXI: Experimental results of magnitrons.

13 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	3	0.11	120	TE_{11}^c	40	2.3		2.2	0.8	Ind. LINAC	0.025	spon.emiss.
[944-954]	8.6	0.45	20 (grating)	TEM_{00} (2nd harm)	0.02	0.15		0.085	0.15	Pulse Line	0.25	Smith-Purcell
	33-36	0.3	80	TE_{11}^c	50	7.1(0.06)	43	1.75	0.4(50)	Pulse Line	0.01	amplifier
	35	0.11	120	TE_{11}^c	80	4.5(3.7)	39	2.2	0.8(1.0)	Ind. LINAC	0.01(0.05)	amplifier
	35	0.17	200	TE_{11}^c	150	2.8(0.75)	45	6.7	0.8(3.0)	Ind. LINAC	0.01	amplifier
Columbia U. NY [955-957]	24	0.05/0.04	34/23	TE_{11}^c/ TM_{11}^c	1	3.3	20	0.58	0.1	Pulse Line	0.15	amplifier
	150	0.18	17	TE_{11}^c	5	5		0.8	0.12	Pulse Line	0.15	oscillator
DLR, Stuttgart [958]	100	0.1	20	TE_{02}^c	1	2		0.5	0.15	Pulse Line	0.03	spon.emiss.
ENEA Frascati [959-963]	85-150	0.61	25	TE_{01}^r	0.0015	0.19		2.3	0.00035	Microtron	5.5	oscillator
EP Palaiseau [964]	120	0.03	20	TE_{11}^c	11.5	6.4		0.6	0.3	Electrostatic	0.02	superrad.
FOM Nieuwegein	206	0.2/0.16	40	HE_{11}^r	0.73(0.5)	5.7(3.9)		1.77	0.0072	Electrostatic	0.5(3.5)	oscillator
[224-234,965]	167	0.16	40	HE_{11}^r	0.36(0.26)	3.1(2.3)		1.61	0.0071	Electrostatic	0.5(3.0)	oscillator
	169	0.16	40	HE_{11}^r	0.1	0.9 (14 with MDC)		1.60	0.007	Electrostatic	36	oscillator
General Electric	2.6	0.04	74.2	TE_{01}^r	1.2	10	6	0.17	0.07	Modulator	5.0	amplifer
Microwave Lab.	2.6-3.7	0.04	74.2	TE_{01}^r	0.9	9.2	10	0.135	0.07	Modulator	5.0	amplifer
Palo Alto [222]	15.7	0.2	23.6	TE_{01}^c	1.65	6	6	0.23	0.125	Modulator	5.0	amplifier
	54	0.2	3.18	TE_{01}^c	0.15	6	10(30)	0.07	0.037	Modulator	4.0	amplifier
IEE,China [235]	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
[966-968]	42.8-47.2	0.03	24	TE_{10}^r	7	12(0.5)		0.5	0.12(3)	Pulse Line	0.015	oscil./CRM
IAP/INP Novosib. / KIT[1)] [969-986]	75	0.10	40	TEM	100	4.2		0.8	3.0	Pulse Line	1.0	oscillator
IAP/U. Strath./HERC [987-989]	28	0.22	16	TE_{11}^c	0.15	0.38		0.2	0.2	Pulse Line	0.0005	superrad.
JINR Dubna/IAP N.Novg.	29.3	0.11	60	TE_{11}^c	6	5(4)		0.8	0.15(0.2)	Ind. LINAC	0.2	oscillator
[990-1002]	30	0.12	60	TE_{11}^c	20 (30)	20(25)		0.8	0.13	Ind. LINAC	0.2 (0.1)	oscillator
	38.2	0.06	60	TM_{12}^c/TE_{11}^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 [1003]	250	0.05	30	TE_{11}^c	0.6	0.5	110	0.6	0.2	Ind. LINAC	0.04	amplifier
ILT/ILE Osaka [1004]	60-110	0.71	60	TE_{01}^r	0.01	0.2		9.0	0.05	RF LINAC	$4x10^{-6}$	oscillator
ISAS, Sagamihara [1005]	11.8	0.09	32.7	TM_{81}^c	3	1		0.43	0.19	Pulse Line	0.4	oscillator
JAEA[2)], Ibaraki [1006,1007]	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 [1008-1010]	27	0.13	32	TM_{11}^c	0.001	0.15		0.4	0.0017	Electrostatic	10-30	oscillator
KEK, Tsukuba [1011-1015]	9.4	0.121	160	TE_{01}^r	100	12.1(5.1)	21	1.5	0.55(1.3)	Ind. LINAC	0.015	amplifier
LANL, Los Alamos [1016]	11.2/16.4			$TM_{02,\,03}$	5	0.125		0.8	5.0	Modulator	1.0	oscil./ampl.
LLNL, Livermore	34.6	0.37	98	TE_{01}^r	1000	34(7.2)	52	3.5	0.85(4.0)	Ind. LINAC	0.02	amplifier
[177,1017-1022]	140	0.17	98	TE_{11}^c	2000	13.3(10)	58	6.0	2.5(3.0)	Ind. LINAC	0.02	amplifier
					500-1000	in up to 50 pulses (2kHz burst)						

[1)]formerly KfK, then FZK, [2)]formerly JAERI,

Institution	Frequency [GHz]	B_w [T]	λ_w [mm]	Mode	Power [MW]	Efficiency [%]	Gain [dB]	Voltage [MV]	Current [kA]	Accelerator	Pulse-Length [µs]	Type
MIT, Cambridge	9.3	0.02	33	TE_{11}^{c}	0.1	10	6	0.18	0.0055	Electrostatic	0.02	amplifier
[739,1023-1026]	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
[1027,1028]	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. [235]	95	0.2	100		10	4		2.5	0.1	Pulse Line	0.25	oscillator
RI, Moscow [1029]	6-25	0.03	48	TE_{11}^{c}/TM_{01}^{c}	10	1.7		0.6	1	Pulse Line	2	spon. emiss.
SIAE, Chengdu [1030]	37	0.125	34.5	TE_{11}^{c}	7.6	5.4		0.5	0.28	Electrostatic	0.015	oscillator
SIOFM, Shanghai [1031,1032]	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 [1033]	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
UESTC, Chengdu [1034,1035]	90	Smith- Purcell		TEM_{00}	0.03	0.03		0.46	0.2	Pulse Line	0.015	oscillator
UNIV. Liverpool [236]	8-12.4	0.1	30	TE_{10}^{r}	$2x10^{-5}$	0.9		0.12	$1.8x10^{-5}$	Electrostatic	CW	oscillator
	9.9	0.017	19	TE_{10}^{r}	10^{-6}	0.2	18	0.05	$1x10^{-5}$	Electrostatic	CW	amplifier
UNIV. Maryland	35	CHI-wiggl.	64	TE_{01}^{coax}	0.0038	0.018	5	0.0011	0.0019	Electrostatic	1	amplifier
[1016,1036,1037]	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 [1038-1040]	120-880	0.15	71.4		0.027	0.5		2-6	0.002	Electrostatic	1-20	oscillator
UNIV. Strathclyde [1041-1043]	8-16	0.11	45	TE_{11}^{c}	1	5.7 (35 with MDC)	23	0.35	0.050	Pulse Line	0.08	amplifier
UNIV. Strath., IAP / KIT[1)]	32.5	0.13	23	TE_{11}^{c}	0.5	5.0		0.3	0.03	Pulse Line	0.1	oscillator
[1044-1058]	37.3	0.06	40	$TEM/TE_{24,1}$ coaxial 2D-1D Bragg cavity	60	10		0.45	1.35	Pulse Line	0.15	oscillator
UNIV. Tel-Aviv [1059-1063]	4.5	0.03	44.4	TE_{01}^{r}	0.0035	6.3		0.07	0.0008	Electrostatic	3	oscillator
	70-110	0.2	44.4	$HE_{10}^{( )}$	0.01	0.7(0.5)		1.1-1.5	0.001(0.0014)	Electrostatic	30000	oscillator
UNIV. Twente [1064]	35	0.19	30	TE_{11}^{c}/TM_{01}^{c}	2.3	0.6		0.5	0.75	Pulse Line	0.1	spon. emiss.

r: rectangular waveguide; c: circular waveguide; [1)]formerly KfK, then FZK

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

Electron beam line (with multi-stage depressed collector)

electron beam current :	12 A
body current :	< 20 mA
gun voltage :	80 kV
type of gun	triode gun, cathode operated in space-charge limited regime
normalized beam emittance	6 p mm mrad (before interaction)
electron beam energy :	1.35 - 2.0 MeV (130 - 250 GHz operation)
acceleration / deceleration :	electrostatic
focusing system	solenoids in period focusing arrays
pulse length	2 ms - 100 ms

Undulator

period	40 mm
pole gap	25 mm
number of periods	34
peak field strength section 1	0.20 T, 20 cells
section 2	0.16 T, 14 cells
drift gap	35 - 60 mm length, adjustable
focusing scheme	equal focusing in x- and y-direction
matching scheme	1/2 cell 1/4 strength, 1/2 cell 3/4 strength

mm-wave system

primary waveguide :	rectangular corrugated
waveguide dimensions :	15 x 20 mm^2
waveguide mode :	HE_{11}
feedback and outcoupling :	via optical beam multiplication in stepped waveguides
feedback coefficient :	adjustable : 0 - 100 %
output window :	Brewster-angle boron-nitride window

mm-wave output power

mm-wave frequency[1)] :	130 - 260 GHz
on-line tunability[2)] :	5 % on ms time-scale
output power :	1 MW
electronic efficiency :	5 %
system efficiency :	> 50 %

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

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

Table XXXIII: Design parameters of the FOM-FEM [224-234,965]. The project was terminated in The Netherlands in the autumn of 2001 and is being rebuilt in Israel.

14 Comparison of Gyrotron and FEM for Nuclear Fusion

Table XXXIV lists a comparison of the main performance parameters and features of gyrotrons and FEMs for ECRH of plasmas in nuclear fusion research. The important advantage of the FEM is its fast and continuous frequency tunability and the possibility of very high peak power but the gyrotron is a much simpler device [4]. Up to now, the cylindrical cavity gyrotron is the only mm-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 (8-170 GHz, 0.1-1.0 MW) [5].

	Gyrotron Oscillator (cyclotron resonance maser axial magnetic field)	Free Electron Maser Oscillator (periodic transverse magnetic field)
1. Beam voltage	low (70 - 95 kV)	high (0.2 - 2 MV)
2. Magnetic field (140 GHz)	high (5.5, 1 st harmonic)	low (0.2 T, wiggler)
3. Frequencies	8 - 1300 GHz	270 MHz - visible
4. Frequency tunability	$\Delta U_{beam}+\Delta U_{mod}$: fast step tuning (5%) ΔB: slow step tuning (35%)	ΔU_{beam}: fast continous tuning (10%) slow mechanincal tuning (50%)
5. Electron beam	magnetron injection gun	Pierce elctron gun, acceleration and deceleration tubes, beam optics
6. Ohmic losses in cavity (1 MW, 140 GHz)	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 (140/170 GHz) present status	high average power 1 MW / 800 s 0.92 MW / 1800 s 0.8 MW / 3600 s (coax. 2.2 MW / 15 ms)	2 GW/20ns but very low duty cycle (LLNL amplifier)
14. Exp. system efficiency without energy recovery	55% 35%	low 5 - 10%
15. Collector loading	relatively low	high
16. Theor. system efficiency with depressed collector	60% (exp. 55%)	60% (exp. 14%)
17. Physical size	3 m x 3 m x 3 m	12 m x 3 m x 3 m
18. Power per unit (170 GHz)	1 MW (coax., 4 MW)	5 MW

Table XXXIV: Comparison of parameters and features of gyrotrons and FEMs for ECRH.

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Gyrotron oscillators are mainly used as high power millimeter wave sources for electron cyclotron resonance heating (ECRH), electron cyclotron current drive (ECCD), stability control and diagnostics of magnetically confined plasmas for generation of energy by controlled thermonuclear fusion. The maximum pulse length of commercially available 140 GHz, megawatt-class gyrotrons employing synthetic diamond output windows is 30 minutes (CPI and European KIT-CRPP-CEA-TED collaboration). The world record parameters of the European 140 GHz gyrotron are: 0.92 MW output power at 30 min. pulse duration, 97.5% Gaussian mode purity and 44% efficiency, employing a single-stage depressed collector (SDC) for energy recovery. A maximum output power of 1.5 MW in 4.0 s pulses was generated with the JAEA-TOSHIBA 110 GHz gyrotron. The Japan 170 GHz ITER gyrotron achieved 1 MW, 800 s at 55% efficiency and holds the energy world record of 2.88 GJ (0.8 MW, 60 min.) and the efficiency record of 57%. The Russian 170 GHz ITER gyrotron achieved 0.8 MW with a pulse duration of 1000 s and 55% efficiency. The short-pulse pre-prototype tube of the European 2 MW, 170 GHz coaxial-cavity gyrotron for ITER achieved at KIT the record power of 2.2 MW at 30% efficiency (without SDC) and 96% Gaussian mode purity. Russian gyrotrons for plasma diagnostics or spectroscopy applications deliver P_{out} = 40 kW with τ = 40 μs at frequencies up to 650 GHz (η > 4%), P_{out} = 5.3 kW at 1 THz (η = 6.1%), and P_{out} = 0.5 kW at 1.3 THz (η = 0.6%). Gyrotron oscillators have also been successfully used in materials processing. Such technological applications require gyrotrons with the following parameters: f > 24 GHz , P_{out} = 4-50 kW, CW, η > 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 gyrotrons for plasma diagnostics. In addition, this work gives a short overview of the present development status of coaxial-cavity multi-megawatt gyrotrons, gyrotrons for technological and spectroscopy applications, relativistic gyrotrons, quasi-optical gyrotrons, fast- and slow-wave cyclotron autoresonance masers (CARMs), gyroklystrons, gyro-TWT amplifiers, gyrotwystron amplifiers, gyro-BWO's, gyropeniotrons, magnicons, gyroharmonic converters, free electron masers (FEMs) and of vacuum windows for such high-power mm-wave sources.

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