



KIT SCIENTIFIC REPORTS 7606

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

Update 2011

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by
Manfred Thumm

Institut für Hochleistungsimpuls- und Mikrowellentechnik
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**STATE-OF-THE-ART OF HIGH POWER GYRO-DEVICES
AND FREE ELECTRON MASERS
UPDATE 2011**

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 0.9 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 $P_{\text{out}} = 40$ kW with $\tau = 40$ μ s at frequencies up to 650 GHz ($\eta \geq 4\%$), $P_{\text{out}} = 5.3$ kW at 1 THz ($\eta = 6.1\%$), and $P_{\text{out}} = 0.5$ kW at 1.3 THz ($\eta = 0.6\%$). Gyrotron oscillators have also been successfully used in materials processing. Such technological applications require gyrotrons with the following parameters: $f \geq 24$ GHz, $P_{\text{out}} = 4$ -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 μ m. 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 50-240 μ m (6.00-1.25 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
manfred.thumm@kit.edu

STATUS DER ENTWICKLUNG VON HOCHLEISTUNGS-GYRO-RÖHREN UND FREI-ELEKTRONEN-MASERN STAND: ENDE 2011

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 Arbeitsgemeinschaft). 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 0,9 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 $P_{\text{out}} = 40 \text{ kW}$ und $\tau = 40 \mu\text{s}$ ($\eta \geq 4\%$), $P_{\text{out}} = 5,3 \text{ kW}$ bei 1 THz ($\eta = 6,1\%$) und $P_{\text{out}} = 0,5 \text{ kW}$ bei 1,3 THz ($\eta = 0,6\%$). Gyrotronoszillatoren finden jedoch auch in der Materialprozeßtechnik erfolgreich Verwendung. Dabei werden Röhren mit folgenden Parametern eingesetzt: $f \geq 24 \text{ GHz}$, $P_{\text{out}} = 4\text{-}50 \text{ kW}$, 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-Durchschnittsleistung 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 50-240 μm (6,60-1,25 THz).

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manfred.thumm@kit.edu

1 Introduction

The possible applications of gyrotron oscillators and other electron cyclotron maser (ECM) fast-wave devices span a wide range of technologies [1-7]. 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) [8-24] 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 [25-44] and stellarators [44-57]. The confining magnetic fields in present day fusion devices are in the range of $B_0=1-3.6$ Tesla. As fusion machines become larger and operate at higher magnetic field ($B_0 \cong 6$ 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 [21,24,26,32,40,45-53,58-64]. 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 [21-24], and 2 MW coaxial-cavity gyrotrons [64,65] 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 [24,32,66]. Frequency tuning has been shown to be possible on quasi-optical Fabry-Perot cavity gyrotrons [67,68] as well as on cylindrical cavity gyrotrons with step tuning (different operating cavity modes) [69-90].

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 [91-95] (Tables II-XII) but also refers to the development of very high frequency gyromonotrons for active plasma diagnostics [96-119], high-frequency sub-millimeter wave spectroscopy [120-159] and medical applications [160-161] (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 [1-5,162-175]. The use of gyrotrons for such technological applications appears to be of interest if one can realize a relatively simple, low cost device which is easy in service (such as a magnetron). Gyrotrons with low magnetic field (operated at the 2nd harmonic of the electron cyclotron frequency), low anode voltage, high efficiency and long lifetime are under development. Mitsubishi in Japan and Gycom in Russia are also employing permanent magnet systems [169,172-182]. 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 sources at 17 to 35 GHz with $P_{\text{out}} = 300$ MW, $\tau = 0.2$ μs and characteristics that will allow approximately 1000 pulses per second will be necessary as drivers [183-185]. 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 [186-195]. 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), gyrotwistrons (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 [3-7,21-24,58-63], 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), KIT Scientific Report 7540 (2010) and 7575 (2011) 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 [17,20,196]

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

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:

$$\Omega_c = \Omega_{c0}/\gamma \quad \text{with} \quad \Omega_{c0} = eB_0/m_0 \quad \text{and} \quad \gamma = [1 - (v/c)^2]^{-1/2} \approx 1 + eV_0 / m_0c^2 = 1 + eV_0/511 \quad (2)$$

where $-e$ and m_0 are the charge and rest mass of an electron, γ is the relativistic factor, B_0 is the magnitude of the guide magnetic field and V_0 is the acceleration voltage in kV. The nonrelativistic electron cyclotron frequency is $f_{c0} / \text{GHz} = 28 B_0 / \text{T}$. 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,

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

The operating frequency of such devices, an example of which is the free electron maser (FEM) [197-201], 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 [8,202]: Richard Twiss in Australia [203], Jürgen Schneider in the US [204] and Andrei Gaponov in Russia [205]. 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 [206]. In early experiments with devices of this type, there was some debate about the generation mechanism and the relative roles of fast-wave interactions mainly producing azimuthal electron bunching and slow-wave interactions mainly producing axial bunching [8,202,207,208]. 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 [209] (where the term "electron cyclotron maser" was apparently coined) and in Russia [210].

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 [211-217], 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):

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

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

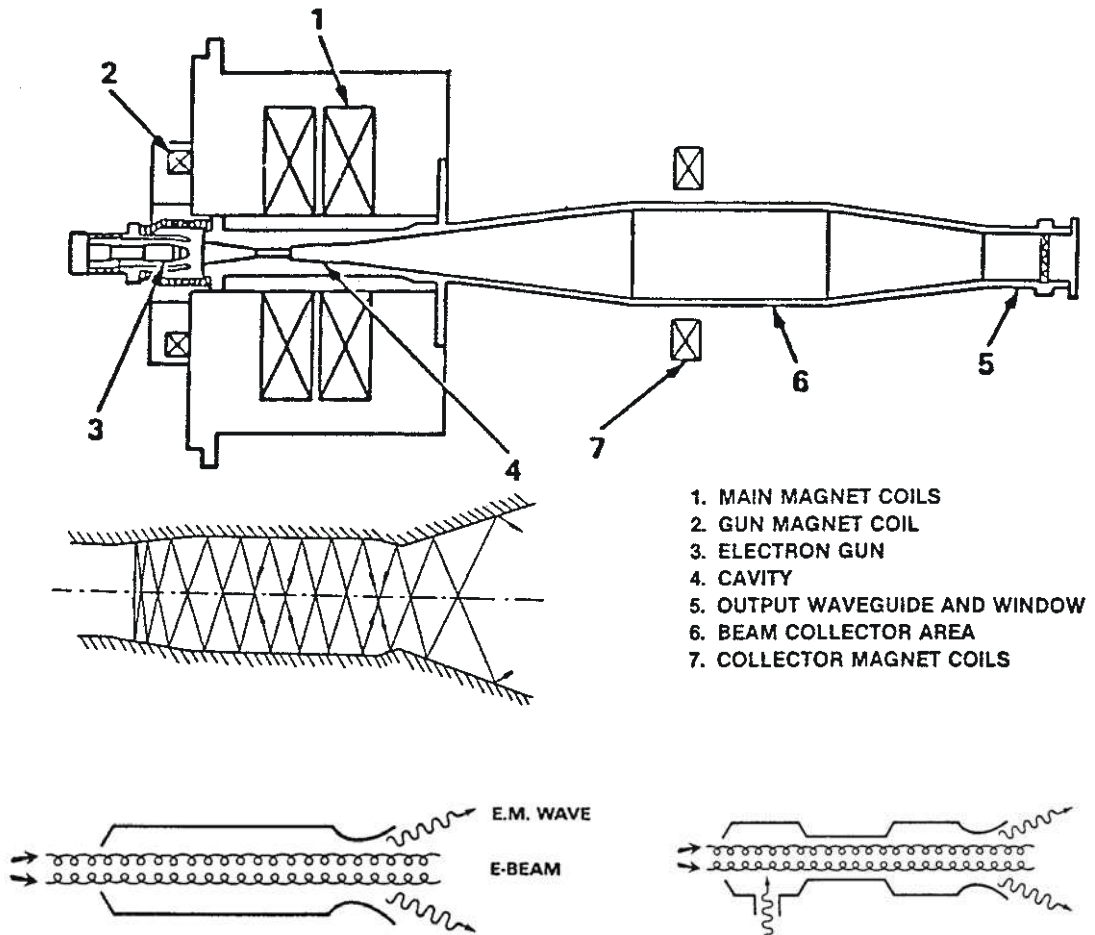
3.1 Gyrotron Oscillator and Gyroklystron Amplifier

Gyrotron oscillators (gyrotrons) were the first ECMs to undergo major development. In September 1964 scientists at IAP Nizhny Novgorod operated the first gyrotron (mode: TE₁₀₁ rectangular cavity, power: 6 W, CW) [17]. In 1966 the term “gyrotron” was coined by Arcady Goldenberg at IAP. 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 [8-16].

Gyrotrons and gyroklystrons are devices which usually utilize only weakly relativistic electron beams ($V_o < 100$ kV, $\gamma < 1.2$) with high transverse momentum (pitch angle $\alpha = v_\perp/v_z > 1$) [214-217]. The wavevector of the radiation in the cavity is almost transverse to the direction of the external magnetic field ($k_\perp \gg k_z$, 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:

$$\omega \cong s\Omega_c, \quad s = 1, 2, \dots \quad (5)$$

In the case of cylindrical cavity tubes (see Figs. 1 and 2) the operating mode is close to cutoff ($v_{ph} = \omega/k_z \gg c$) 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 [210-217]. 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 $k_\perp \gg k_z$ (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 [215-224] 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 [225]. 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 [8-16, 177-182, 211-217].



- 1. MAIN MAGNET COILS
- 2. GUN MAGNET COIL
- 3. ELECTRON GUN
- 4. CAVITY
- 5. OUTPUT WAVEGUIDE AND WINDOW
- 6. BEAM COLLECTOR AREA
- 7. COLLECTOR MAGNET COILS

Fig. 1: Schematic of VARIAN CW gyrotron oscillator [13,18] and scheme of irregular waveguide cavities of gyromonotron oscillator (left) and gyrokystron amplifier [212,213].

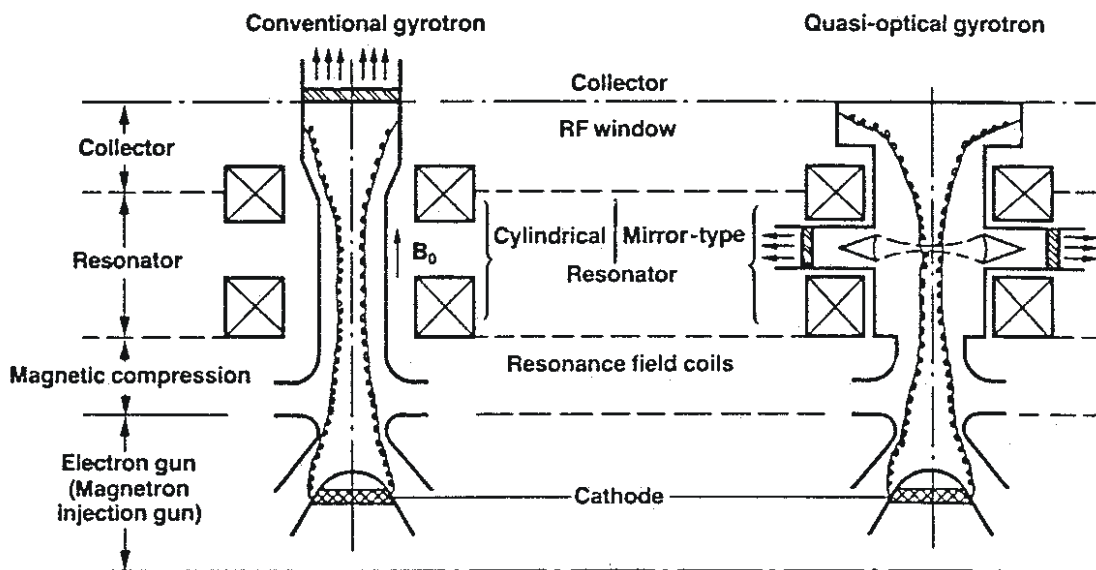


Fig. 2: Principle of a conventional gyrotron with cylindrical resonator and of a quasi-optical gyrotron with mirror resonator [67,68].

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.

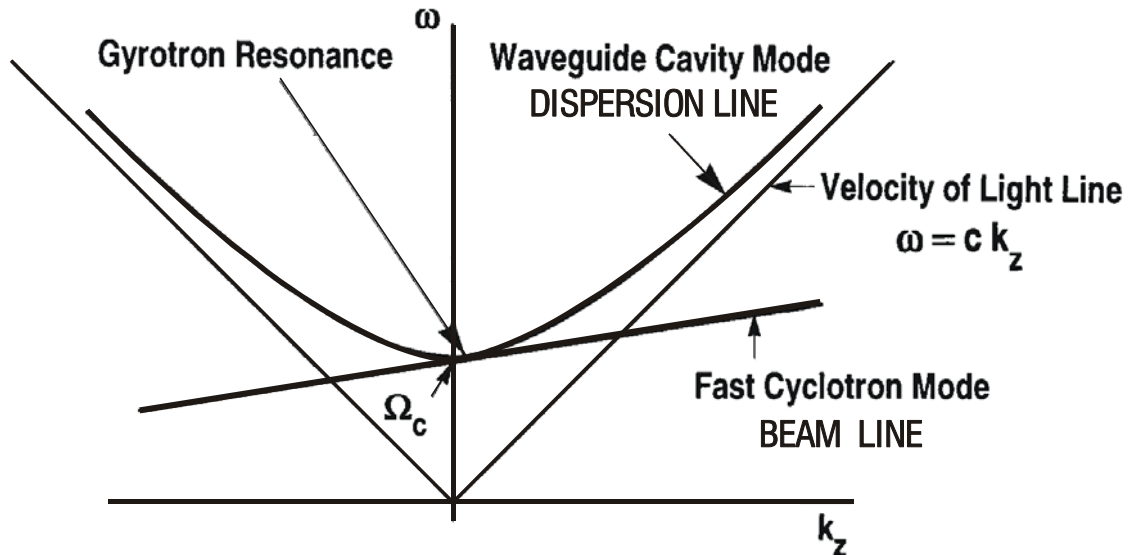


Fig. 3: Dispersion diagram of gyrotron oscillator (fundamental resonance).

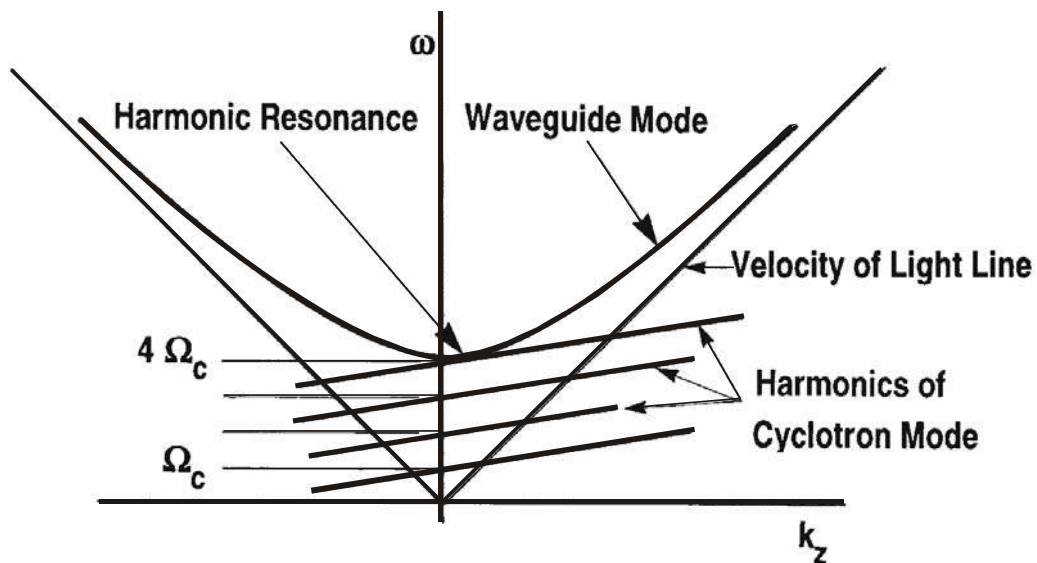


Fig. 4: Dispersion diagram of harmonic frequency gyrotron oscillator.

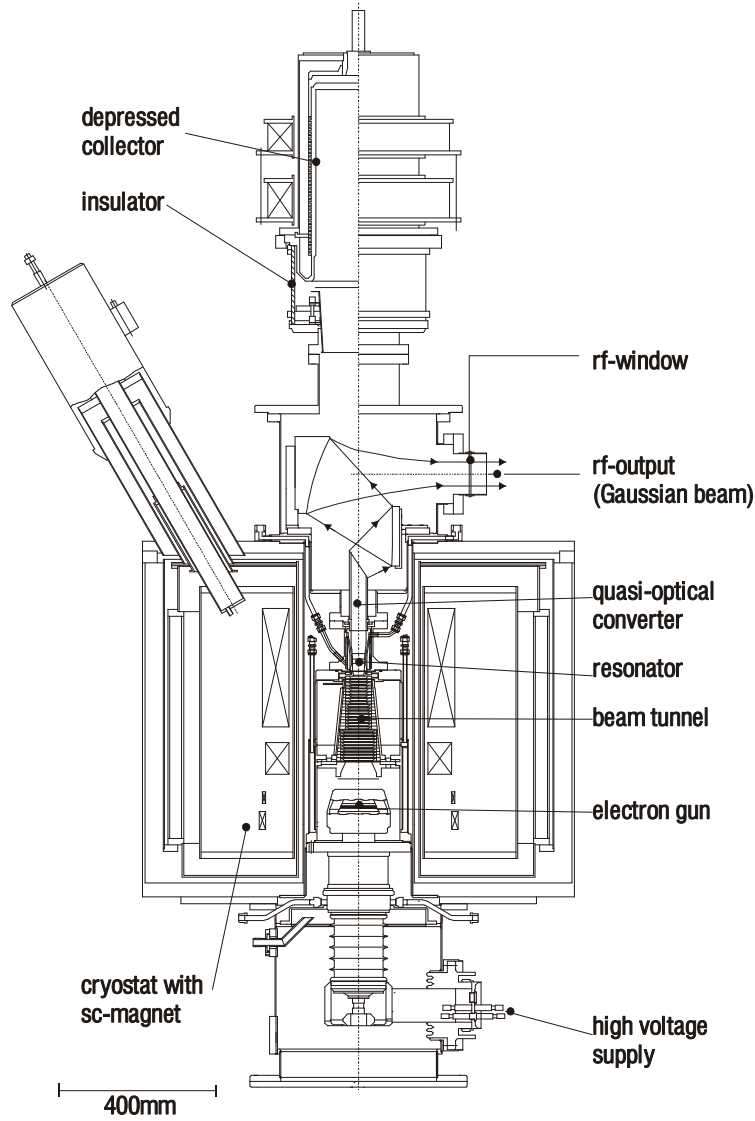


Fig. 5: Schematic layout of modern high-order volume mode gyrotron with quasi-optical mode converter and single-stage depressed collector.

3.2 Cyclotron Autoresonance Maser (CARM)

In a gyrotron with a highly relativistic beam ($\geq 1\text{MeV}$), 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

$$\omega \cong k_z v_z + s\Omega_c \quad (6)$$

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 [17,196]. Fig. 6 shows how the Brillouin diagram of the fast cyclotron wave changes during the autoresonance

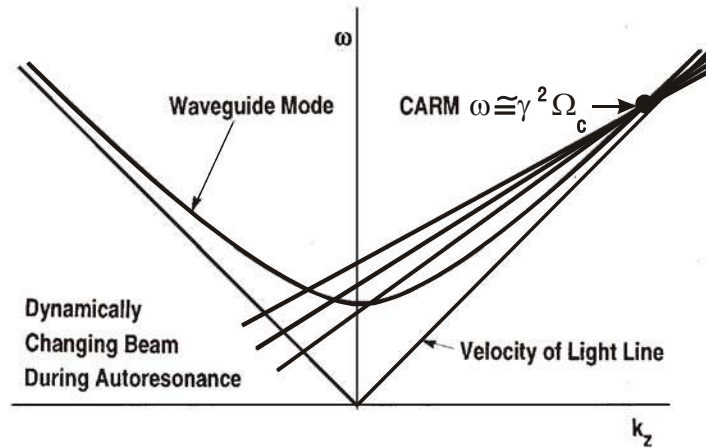


Fig. 6: Dispersion diagram of the cyclotron autoresonance maser (CARM).

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) [196] 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_0 . Since the axial bunching mechanism can substantially offset the azimuthal bunching the total energy of the beam and not only the transverse component is available for RF conversion.

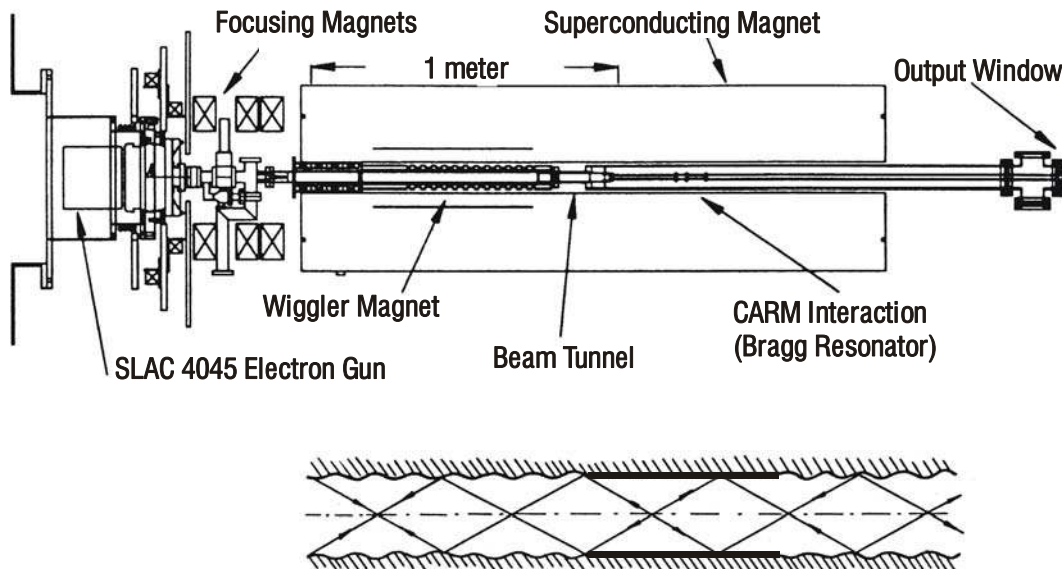


Fig. 7: Schematic of the long-pulse MIT CARM oscillator experiment [226] and scheme of a Bragg resonator [196].

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% [196,226].

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 [227-230], 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

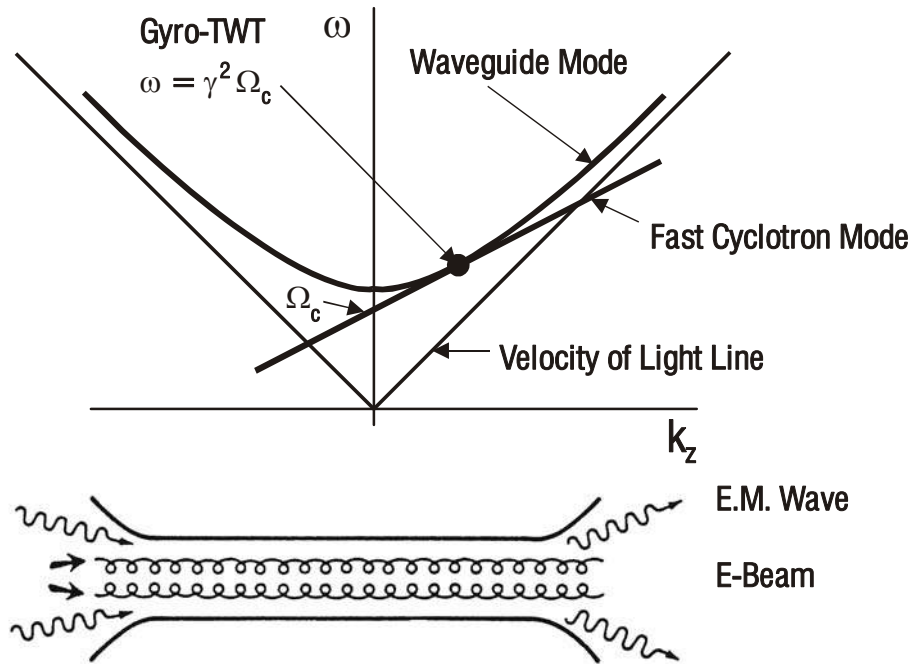


Fig. 8: Dispersion diagram and scheme of interaction circuit of Gyro-TWT amplifier.

($\omega/k_z \gg c$), 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 [231-234].

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) [235,236].

The gyrotwystron [8], a hybrid device, is derived from the gyroklystron by extending the length of the drift section and replacing the output cavity with a slightly 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 bandwidth 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 [237]. 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

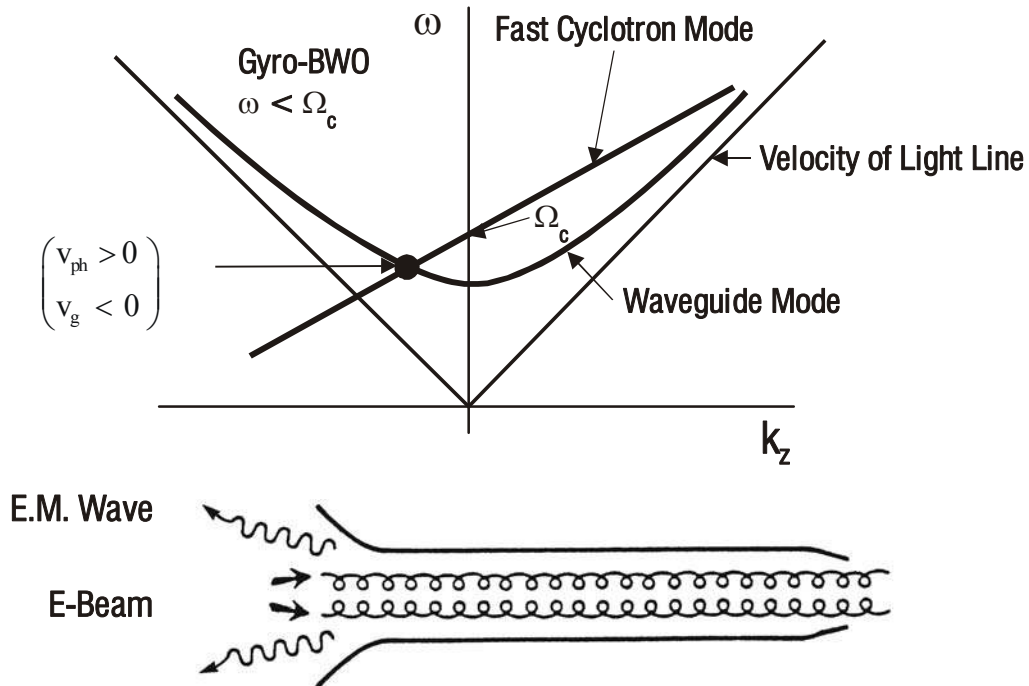


Fig. 9: Dispersion diagram and scheme of interaction circuit of Gyro-BWO.

thus of the beam acceleration voltage V_0 . 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_0 in place of B_0 . However, there is a Doppler down shift in frequency ($\Omega_c/2 < \omega < \Omega_c$), so that very high magnetic fields are required for high frequency operation.

3.5 Overview on Gyro-Devices

Bunching of electrons in the gyrotron oscillator discussed in section 3.1 has much in common with that in conventional linear electron beam devices, namely, monotron, klystron, TWT, twystron and BWO [8]. 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 ($s=1$) [8]. 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.

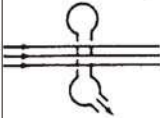
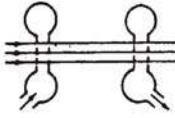

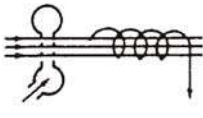
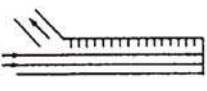
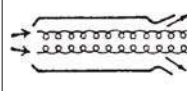
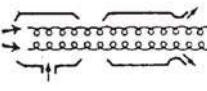
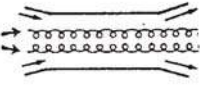
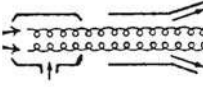
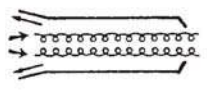


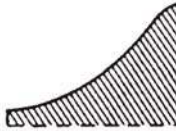


| | | | | | |
|--------------------------|--|--|---|---|---|
| "O" TYP DEVICES |  MONOTRON |  KLYSTRON |  TWT |  TWYSTRON |  BWO |
| TYPE OF GYRO-DEVICE |  GYRO-MONOTRON |  GYRO-KLYSTRON |  GYRO-TWT |  GYRO-TWYSTRON |  GYRO BWO |
| MODEL RF-FIELD STRUCTURE |  |  |  |  |  |
| MODEL ORBITAL EFFICIENCY | 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 [8].

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 [211,238]. 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 [212-215,239].

4 Magnicons and Gyroharmonic Converters

The magnicon is a member of the class of scanning-beam amplifier tubes [15,240,241]. 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 bremsstrahlung 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 indentially, very high efficiencies can be achieved.

Recently, higher perveance versions of the magnicon have been developed [241], 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 [242]. This match allows efficient power transfer into the 7th harmonic from a fundamental frequency wave that energizes an electron beam via cyclotron autoresonance acceleration (CARA). Theory indicates that high conversion efficiency can be obtained for a high quality beam injected into CARA, and when mode competition can be controlled.

Generation of 0.5 MW power (3 μ s pulse duration, 5 % efficiency) at 8.57 GHz (3rd harmonic of 2.856 GHz) in the TE_{31} mode has been observed in experiments using a 350 kV, 30 A electron beam [242-244].

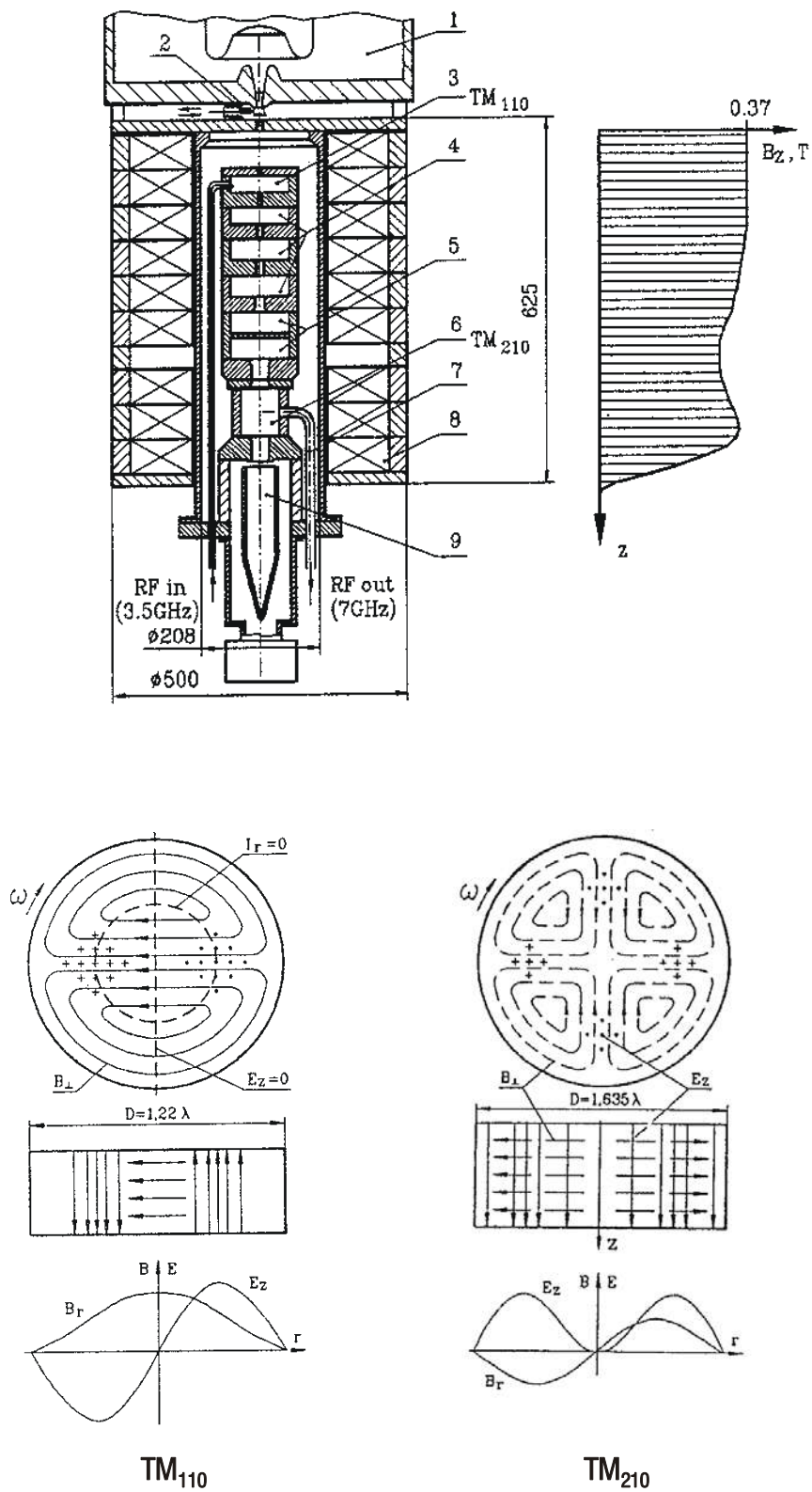


Fig. 10: Schematic layout of the magnicon: 1 – electron source; 2 – vacuum valve; 3 – drive cavity; 4 – gain cavity; 5 – penultimate cavity; 6 – output cavity; 7 – waveguide (x2); 8 – solenoid; 9 – collector [240].

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 [196,201,212,213]. To achieve this spectral versatility, FELs exploit relativistic beam technology to upshift the electron "wobble" 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 [245]: 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 [8,17,196]. 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) [246].

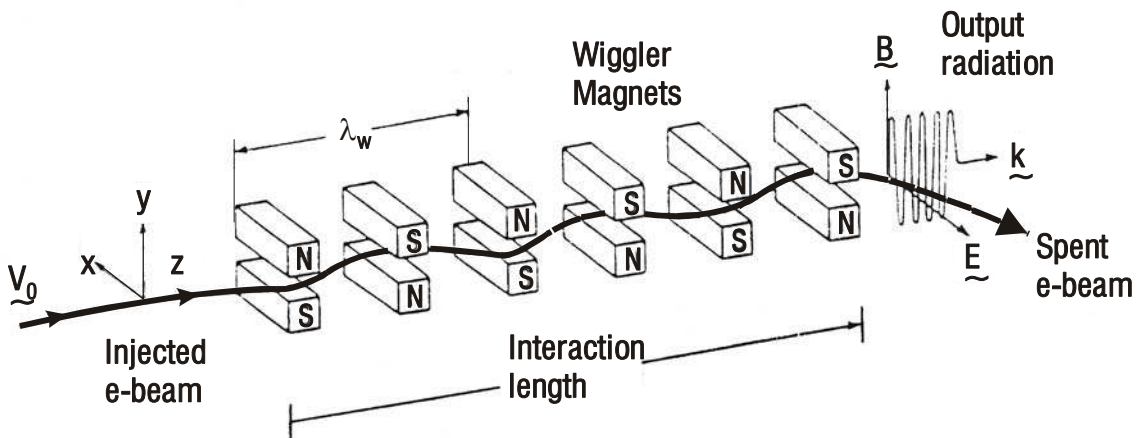


Fig. 11: The basis FEM configuration. Electrons in an injected electron beam undulate in the periodic magnetic field of the wiggler.

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 severe problems, and even higher frequencies are quite feasible [4,247-258]. 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 [247-257] was terminated in the autumn of 2001.

The highest CW power generated by a FEM is 36 W (15 Hz) [259] 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% [260-266]. 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% [267,268].

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 with a maximum gain of 40% [269,270].

6 Gyrotron Oscillators and Microwave Vacuum Windows for Plasma Heating

| Institution | Frequency | Mode | | Power | Efficiency | Pulse length |
|--|-------------------------|------------------------------------|------------------------------------|----------------------|------------------|-------------------|
| | [GHz] | cavity | output | [MW] | [%] | [s] |
| ABB, Baden [215,271] | 8 | TE ₀₁ | TE ₀₁ | 0.35 | 35 | 0.5 |
| | 39 | TE ₀₂ | TE ₀₂ | 0.25 | 42 | 0.1 |
| CPI ¹⁾ , Palo Alto [13,18,272-287] | 8 | TE ₂₁ | TE ₁₀ | 0.5 (dual output) 33 | | 1.0 |
| | 28,35 | TE ₀₂ | TE ₀₂ | 0.2 | 37 | CW |
| | 53.2,56,60,70 | TE _{01/02} | TE ₀₂ | 0.23 | 37 | CW |
| | | 70.15 | TE _{10,3} | TEM ₀₀ | 0.6 | 47 (SDC) |
| | 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 |
| CPI ¹⁾ , NIFS Palo Alto, Toki [54,55,273-277,288-291] | 95.3 | TE _{22,6} | TEM ₀₀ | 0.62 (1.92) | 41 (40) (SDC) | 15 (0.005) |
| | 84 | TE _{15,3} | TEM ₀₀ | 0.5(0.4) | 29 | 2.0(10.5) |
| GYCOM, IAP Nizhny Novgorod [14,70,71,83-95,292-302] | | | | 0.1 | 14 | CW |
| | | | | 0.59(0.25) | 41 (SDC) | 0.001(0.2) |
| | | | | 0.25 | 32 (SDC) | 0.2 |
| | 5 | TE ₀₁ | TE ₀₁ | 0.23 | 26 | 0.1 |
| | 28 | TE ₄₂ | TEM ₀₀ | 0.5 | 36 | 0.5 |
| | 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 [212] | 60 | TE ₀₂ | TE ₀₂ | 0.2 | 35 | 0.1 |
| IAP, Nizhny Novgorod [303] | 25(2Ω _c) | TE ₀₃ | TE ₀₃ | 0.8 | 40 (twin e-beam) | 0.0001 |
| IECAS, Beijing [304-306] | 24.1 | TE ₀₁ | TE ₀₁ | 0.15 | 24 | 0.02 |
| | 34.3(2Ω _c) | TE _{02/03} | TE ₀₃ | 0.2 | 30 | 0.02 |
| | | 94 | TE ₀₂ | TEM ₀₀ | 0.015 | 18 |
| LAP/INPE, Sao Paulo [307] | 24.2 | TE ₁₂ | TE ₁₂ | 0.0058 | 16 | 0.000015 |
| | 30.4 | TE ₂₂ | TE ₂₂ | 0.0063 | 18.5 | 0.000015 |
| MITSUBISHI, Amagasaki KYOTO UNIV. [308] | 88 | TE _{8,2} | TEM ₀₀ | 0.35 | 29 | 0.1 |
| NEC, Kawasaki [309] | 35 | TE ₀₁ | TE ₀₁ | 0.1 | 30 | 0.001 |
| NRL, Washington D.C. [212,310] | 35 | TE ₀₁ | TE ₀₁ | 0.15 | 31 | 0.02 |
| | 35 | TE ₀₄ | TE ₀₄ | 0.475 | 38 | 0.001 |
| | 35 | TE ₂₄ | TE ₂₄ | 0.43 | 40 | 0.001 |
| PHILIPS ²⁾ , Hamburg [311] | 70 | TE ₀₂ | TE ₀₂ | 0.14 | 30 | CW |
| SPbSTU, St. Petersburg KIT ³⁾ Karlsruhe [312-319] | 74.2 | TE _{12,3} | TE _{12,3} | 0.1 | 44 | 0.00005 |
| THALES ED ⁴⁾ , Velizy [215,320] | 8 | TE ₅₁ | TE ₅₁ | 1.0 | 45 | 1.0 |
| TOSHIBA, Otawara [57,321-326] | 35 | TE ₀₂ | TE ₀₂ | 0.2 | 43 | 0.15 |
| | 28 | TE ₀₂ | TE ₀₂ | 0.2 | 35.7 | 0.075 |
| | | TE _{4,2} | TEM ₀₀ | 0.57 | 40 | 0.01 |
| | | TE _{8,3} | TEM ₀₀ | 1.05 (0.8) | 30 (40) | 0.001 |
| | 41 (56) | TE ₀₂ | TE ₀₂ | 0.2 | 31.3 (32.9) | 0.1 |
| | 70 | TE ₀₂ | TE ₀₂ | 0.025 | 28.4 | 0.001 |
| | 77 | TE _{18,6} | TEM ₀₀ | 1.8 | 38 (SDC) | 1.0 |
| | | | 1.6 | 40 (SDC) | 1.8 | |
| | | | 1.2 | 38 (SDC) | 10.0 | |
| | | | 0.3 | 36 (SDC) | 900 | |
| UESTC, Chengdu [327-331] | 35(3Ω _c) | TE ₅₁ /TE ₅₂ | TE ₅₂ | 0.147 | 10.2 | 0.0001 PM, 100 kg |
| | 70,94(2Ω _c) | TE ₀₂ /TE ₀₃ | TE ₀₃ | 0.1(0.12) | 20(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] |
|---|----------------------|---------------------|----------------------|---------------|-------------------|---------------------|
| CPI¹⁾, Palo Alto [13,273-277,286,332-346] | 106.4(2 Ω_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 | |
| KIT²⁾, Karlsruhe [72-78,347-360] | 117.9 | TE _{19,5} | TEM ₀₀ | 1.55 | 31 | 0.007 |
| | | | | 1.55 | 49.5 (SDC) | 0.007 |
| | 132.6 | TE _{9,4} | TE _{9,4} | 0.42 | 21 | 0.005 |
| GYCOM-M, IAP Moscow, N. Novgorod [14,217,297,361-370] | 110 | TE _{19,5} | TEM ₀₀ | 1.2 | 40 | 0.0001 |
| | | | | 1.0 | 65(SDC) | 0.0001 |
| | | | | 0.93 | 36 | 2.0 |
| | | | | 0.5 | 35 | 5.0 |
| | | | | 0.35 | 33 | 10.0 |
| GYCOM, IAP Nizhny Novgorod [14,70,71,79-90,292-297, 371-375] | 104 | TE _{18,7} | TEM ₀₀ | 0.98 | 46.5 (SDC) | 0.5 |
| | 105 | TE _{17,6} | TEM ₀₀ | 0.85 | 50 (SDC) | 10.0 |
| | 106.4 | TE _{15,4} | TEM ₀₀ | 0.5 | 33 | 0.2 |
| | | | | 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 |
| JAEA³⁾, TOSHIBA Naka, Otawara [21,376-396] | 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 [397,398] | 120 | TE _{02,03} | TE ₀₃ | 0.16 | 25 | 0.06 |
| | | | | 1.02 | 32.5 | 0.0002 |
| | 120 | TE _{15,2} | TE _{15,2} | 0.46 | 30 | 0.1 |
| | | | | 0.25 | 30 | 0.21 |
| THALES ED⁴⁾, Velizy [215,320] | 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 ED⁴⁾, CEA,CRPP, KIT [399-409] | 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 ($100 \text{ GHz} \leq f < 140 \text{ GHz}$, $\tau \geq 0.1 \text{ ms}$).

| Institution | Frequency [GHz] | Mode cavity | Mode output | Power [MW] | Efficiency [%] | Pulse length [s] | |
|---|--------------------|---------------------|--------------------|--------------------|-------------------|---------------------|-------------|
| CPI¹⁾, Palo Alto [13,18,273-277,286,341-345, 410-413] | 140 | TE _{02,03} | TE ₀₃ | 0.1 | 27 | CW | |
| | 140 | TE _{15,2} | TE _{15,2} | 1.04 | 38 | 0.0005 | |
| | | | | 0.32 | 31 | 3.6 | |
| | | 140.2 | TE _{28,7} | TEM ₀₀ | 0.2 (0.4) | 31 | avg. (peak) |
| | | | | | 0.92 | 35 (SDC) | 0.003 |
| | | | | 0.9 | 33 (SDC) | 1800 | |
| KIT²⁾, PHILIPS³⁾ [215,414] | 140.8 | TE ₀₃ | TE ₀₃ | 0.12 | 26 | 0.4 | |
| | 140.2 | TE _{10,4} | TE _{10,4} | 0.69 | 28 | 0.005 | |
| 140.2 | | | | TE _{10,4} | TEM ₀₀ | 0.60 | 27 |
| | | | | | | | 0.50 |
| | | | | 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 | |
| KIT²⁾, CRPP, THALES ED⁴⁾, CEA [6,50-53,62-64,402, 430-463] | 139.8 | TE _{28,8} | TEM ₀₀ | 1.0 | 50 (SDC) | 12 | |
| | | | | 0.92 | 44 (SDC) | 1800 | |
| GYCOM, IAP Nizhny Novgorod [14,79-90,293-297,363-370, 375,464-495] | 140 | TE _{22,6} | TEM ₀₀ | 0.96 | 36 | 1.2 | |
| | | | | 0.54 | 36 | 3.0 | |
| | | | | 0.26 | 36 | 10 | |
| | | | | 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 | 1.2 | 52 (SDC) | 100 | |
| | | | | 1.0 | 55 (SDC) | 570 | |
| | | | | | 0.9 | 55 (SDC) | 1000 |
| | 170 | TE _{28,12} | TEM ₀₀ | 1.44 | 41 (SDC) | 0.1 | |
| 2.1 | | | | 35 | 0.0001 | | |
| GYCOM-N, IAP Nizhny Novgorod [14,70,71,292-295,301, 368-370,373,374,464,479] | 140 | TE _{22,6} | TEM ₀₀ | 0.8 | 32 | 0.8 | |
| | | | | 0.88 | 50.5(SDC) | 1.0 | |
| | | | | 0.55 | 33 | 2.0 | |
| | 140 | TE _{22,10} | TEM ₀₀ | 0.99 | 47 (SDC) | 0.5 | |
| | 158.5 | TE _{24,7} | TEM ₀₀ | 0.5 | 30 | 0.7 | |
| JAEA⁵⁾, TOSHIBA Naka, Otawara [21,381-389,395,396,496-522] | 170 | TE _{22,6} | TEM ₀₀ | 0.45 | 19 | 0.05 | |
| | | | | 0.25 | 19 | 0.4 | |
| | | | | | 0.25 | 32 (SDC) | 0.4 |
| | 170.1 | TE _{31,8} | TE _{31,8} | 1.15 | 29 | 0.0004 | |
| | | | | 1.3 | 32 | 0.003 | |
| | 170 | TE _{31,8} | TEM ₀₀ | 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 | |
| | 170 | TE _{31,11} | TEM ₀₀ | 1.0 | 38 (SDC) | 5.0 | |
| NIFS, TOSHIBA Toki, Otawara [54-57,291,523,524] | 168 | TE _{31,8} | TEM ₀₀ | 0.52 | 19 | 1.0 | |
| | | | | 0.52 | 30 (SDC) | 1.0 | |

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 ($f \geq 140$ GHz, $\tau \geq 0.1$ ms).

| Institution | Frequency [GHz] | Mode | | Power [MW] | Efficiency [%] | Corrug.Cavity | |
|---|------------------------------|---------------------|---------------------|----------------------|-------------------|---------------|-------|
| | | cavity | output | | | inner | outer |
| KIT ¹⁾ Karlsruhe [6,22,62-65,424-430,446, 525-547] Pulse length ≤ 100 ms | 137.78 | TE _{27,16} | TE _{27,16} | 1.03 | 24.3 | yes | no |
| | 139.96 | TE _{28,16} | TE _{28,16} | 1.17 | 27.2 | yes | no* |
| | | | TEM ₀₀ | 0.95 | 20 | yes | no |
| | | | | 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 |
| | EGYC ²⁾ [548-572] | 167.14 | TE _{32,17} | TEM ₀₀ | 1.22 | 25.6 | yes |
| 170 | | TE _{34,19} | TEM ₀₀ | 2.2 | 30 | yes | no |
| | | | | 2.0 | 46 (SDC) | yes | no |
| | | | | | | | |
| IAP, Nizhny Novgorod [12,14,294,297,573-581] Pulse length ≤ 0.1 ms | 45 | TE _{15,1} | TE _{15,1} | 1.25 | 43 | no | no |
| | 100 | TE _{21,18} | TE _{21,18} | 1.0 | 35 | yes | no |
| | | | | 0.5 | 20 | no | no |
| | 100 | TE _{25,13} | TE _{25,13} | 2.1 | 30 | no | no |
| | | | | 1.6 | 38 | no | no |
| | 103 | TE _{22,13} | TE _{22,13} | 1.0 | 40 | yes | yes |
| | | | | 0.7 | 30 | yes | no |
| | | | | 0.3 | 14 | no | no |
| | 110 | TE _{17,7} | TE _{17,7} | 0.7 | 25 | no | no |
| | 110 | TE _{20,13} | TE _{20,13} | 1.15 | 35 | yes | no |
| | 110 | TE _{21,13} | TE _{21,13} | 1.0 | 35 | yes | no |
| | 140 | TE _{28,16} | TE _{28,16} | 1.5 | 33.5 | yes | no* |
| | | | | 1.15 | 50 (SDC) | yes | no |
| | | | 1.17 | 35.2 | yes | yes | |
| | | | 1.1 | 30 | yes | no | |
| | | | (dual-beam output) | | | | |
| 224 (2 Ω_c) | TE _{33,8} | TE _{33,8} | 0.1 | 11 | yes | no | |
| IAP, KIT ¹⁾ Karlsruhe [525] Pulse length 30 μ s | 133 | TE _{27,15} | TE _{27,15} | 1.3 | 29 | no | no |
| | 140 | TE _{28,16} | TE _{28,16} | 1.0 | 23 | no | no |
| MIT, Cambridge [582-584] Pulse length 3 μ s | 137 | TE _{25,11} | TEM ₀₀ | 0.5 | 7.5 | no | no |
| | 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 μ s – 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 [585,586].

| Institution | Frequency | Mode | | Power | Efficiency | Pulse length | |
|---|---|-------------------------------------|--------------------|-------------------|---------------|------------------|--------|
| | [GHz] | cavity | output | [MW] | [%] | [s] | |
| CPI¹⁾, Palo Alto [272-287,336-345,410-413] | 8 | TE ₂₁ | TE ₁₀ | 0.4 | 26.6 | 0.0005 | |
| | | (dual rectangular waveguide output) | | 0.4 | 34.2 (SDC) | 0.0005 | |
| | 70.15 | TE _{10,3} | TEM ₀₀ | 0.6 | 47 (SDC) | 2.25 | |
| | 94.9 | TE ₆₂ | TEM ₀₀ | 0.12 | 50 (SDC) | CW | |
| | 95.3 | TE _{22,6} | TEM ₀₀ | 0.62 (1.92) | 41(40) (SDC) | 15 (0.005) | |
| | 110 | TE _{22,6} | TEM ₀₀ | 1.28 | 42.3 (SDC) | 0.001 | |
| | | | | 0.52 | 29 (SDC) | 10 | |
| | 140.2 | TE _{27,8} | TEM ₀₀ | 0.92 | 35(SDC) | 0.003 | |
| | | | | 0.9 | 33(SDC) | 1800 | |
| | CPI¹⁾, NIFS Palo Alto, Toki [54-57,276] | 84 | TE _{15,3} | TEM ₀₀ | 0.5 | 29 | 2.0 |
| | | | | 0.59 | 41 (SDC) | 0.001 | |
| | | | | 0.25 | 32 (SDC) | 0.2 | |
| KIT²⁾, Karlsruhe [22,72-78,347-360,419-430] | 117.9 | TE _{19,5} | TEM ₀₀ | 1.55 | 49.5 (SDC) | 0.007 | |
| | 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 | |
| KIT²⁾, CRPP, THALES ED³⁾, CEA [6,50-53,62-64,402, 430-463] | 162.3 | TE _{25,7} | TEM ₀₀ | 1.48 | 50 (SDC) | 0.007 | |
| | 139.8 | TE _{28,8} | TEM ₀₀ | 1.0 | 50 (SDC) | 12 | |
| | | | | 0.92 | 43 (SDC) | 1800 | |
| GYCOM, IAP Nizhny Novgorod [295-297,299-302,364,365, 370,372] | 68 (70) | TE _{9,3} | TEM ₀₀ | 0.5 (0.68) | 50 (48) (SDC) | 1.0 (3.0) | |
| | 75 | TE _{11,5} | TEM ₀₀ | 0.8 | 70 (SDC) | 0.1 | |
| | 82.7 | TE _{10,4} | TEM ₀₀ | 0.65 | 38 | 3.0 | |
| | | | | 0.65 | 53 (SDC) | 0.03 | |
| | | | | 0.2 | 52 (SDC) | CW | |
| | 84 | TE _{12,5} | TEM ₀₀ | 0.88 (0.2) | 50 (SDC) | 3.0 (CW) | |
| | 104 | TE _{18,7} | TEM ₀₀ | 0.98 | 46.5 (SDC) | 0.5 | |
| | 110 | TE _{19,5} | TEM ₀₀ | 1.0 | 65 (SDC) | 0.0001 | |
| | 140 | TE _{22,6} | TEM ₀₀ | 0.8 | 32 | 0.8 | |
| | | | | 0.88 | 50.5 (SDC) | 1.0 | |
| | 140 | TE _{22,10} | TEM ₀₀ | 0.99 | 47 (SDC) | 0.5 | |
| | GYCOM, IAP Nizhny Novgorod [79-90,301,477-495] | 140 | TE _{22,8} | TEM ₀₀ | 1.7 | 42 | 0.0001 |
| | | | | 0.95 | 52(SDC) | 10 | |
| | 170 | TE _{25,10} | TEM ₀₀ | 1.2 | 52 (SDC) | 100 | |
| | | | | 1.0 | 55 (SDC) | 570 | |
| | | | 0.9 | 55 (SDC) | 1000 | | |
| 170 | TE _{28,12} | TEM ₀₀ | 1.44 | 41 (SDC) | 0.1 | | |
| NRL, Washington D.C. [587] | 115 | QOG | TEM ₀₀ | 0.43 | 12.7 (SDC) | 10 ⁻⁵ | |
| | | | | 0.20 | 16.1 (SDC) | 10 ⁻⁵ | |
| JAEA⁴⁾, TOSHIBA Naka, Otawara [376-396,496-522] | 110 | TE _{22,2} | TEM ₀₀ | 0.61 | 50 (SDC) | 0.05 | |
| | | | | 0.35 | 48 (SDC) | 5.0 | |
| | 110 | TE _{22,6} | TEM ₀₀ | 1.5 | 45 (SDC) | 4.0 | |
| | | | | 1.0 | 38 (SDC) | 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 Toki, Otawara [54-57,291, 323-326,523,524] | 170 | TE _{31,11} | TEM ₀₀ | 1.0 | 47 (SDC) | 5.0 | |
| | 77 | TE _{18,6} | TEM ₀₀ | 1.2 | 38 (SDC) | 10.0 | |
| | 168 | TE _{31,8} | TEM ₀₀ | 0.52 | 19 | 1.0 | |
| | | | 0.52 | 30 (SDC) | 1.0 | | |

SDC: Single-stage Depressed Collector;

QOG: Quasi-Optical Gyrotron

¹⁾ formerly VARIAN, ²⁾ formerly KfK, then FZK, ³⁾ formerly Thomson TE ⁴⁾ formerly JAERITable VI: Present development status of high frequency gyrotron oscillators with conventional cylindrical or quasi-optical cavity and single-stage depressed collector (SDC) ($\tau \geq 10 \mu\text{s}$).

| Institution | Frequency [GHz] | Mode cavity | Mode output | Power [MW] | Efficiency [%] | Pulse length [s] | | |
|---|---|--|--------------------|-------------------|----------------|------------------|----------------|-------------|
| KIT¹⁾, Karlsruhe [72-78,90,352, 355-360,425-430, 457-459] | 114.2 | TE _{18,5} | TEM ₀₀ | 0.85 | 23 | 0.001 | | |
| | 117.9 | TE _{19,5} | TEM ₀₀ | 1.0 | 27 | 0.001 | | |
| | | | | 1.55 | 49.5 (SDC) | 0.007 | optimized | |
| | 121.6(119.5) | TE _{20,5} (TE _{19,7}) | TEM ₀₀ | 1.0(0.88) | 27(23) | 0.001 | | |
| | 125.3(124.1) | TE _{21,5} (TE _{20,7}) | TEM ₀₀ | 1.0(0.89) | 27(24) | 0.001 | | |
| | 128.9 | TE _{22,5} | TEM ₀₀ | 0.9 | 24.5 | 0.001 | | |
| | 132.6(130.9) | TE _{20,6} (TE _{22,7}) | TEM ₀₀ | 0.85(0.9) | 23(24) | 0.001 | | |
| | 136.2 | TE _{21,6} | TEM ₀₀ | 0.9 | 24.5 | 0.001 | | |
| | 140.1(140.0) | TE _{22,6} (TE _{22,8}) | TEM ₀₀ | 1.0(1.2) | 27(28) | 0.001 | | |
| | | | | 1.6 | 60 (SDC) | 0.007 | optimized | |
| | 143.7(143.3) | TE _{23,6} (TE _{23,8}) | TEM ₀₀ | 1.1(1.2) | 30(29) | 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(155.9) | TE _{23,7} (TE _{24,9}) | TEM ₀₀ | 0.95(0.98) | 26(26) | 0.001 | | |
| | 158.5(159.2) | TE _{24,7} (TE _{25,9}) | TEM ₀₀ | 1.1(1.0) | 30(27.2) | 0.001 | | |
| | 162.3(162.5) | TE _{25,7} (TE _{26,9}) | TEM ₀₀ | 1.0(0.99) | 27(27.3) | 0.001 | | |
| | | | | 1.48 | 50 (SDC) | 0.007 | optimized | |
| | 166.0(165.9) | TE _{26,7} (TE _{27,9}) | TEM ₀₀ | 1.0(0.95) | 26(26) | 0.001 | | |
| | GYCOM, IAP Nizhny Novgorod [39,42,70,71,79-89, 297-301,370,373- 375,486,487,588] | 71.5 | TE _{10,5} | TEM ₀₀ | 0.8 | 56 | 0.15 | 3f-Gyrotron |
| | | 74.8 | TE _{11,5} | TEM ₀₀ | 0.8 | 56 | 0.15 | with |
| 78.1 | | TE _{12,5} | TEM ₀₀ | 0.8 | 56 | 0.15 | Brewster wind. | |
| 121.5 | | TE _{20,5} | TEM ₀₀ | 0.5 | 30 | 0.0001 | | |
| 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 | | |
| | | | | 0.85 | 50 (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 | | | |
| JAEA²⁾, TOSHIBA Naka, Otawara [517,520,522] | 136.8 | TE _{25,9} | TEM ₀₀ | 1.30 | 26 | 0.0005 | 2f-Gyrotron | |
| | | | | 0.6 | 37 (SDC) | 10 | | |
| | 170 | TE _{31,11} | TEM ₀₀ | 1.30 | 27 | 0.0005 | | |
| | | | | 1.0 | 47 (SDC) | 5.0 | | |
| | | | 0.55 | 24 (SDC) | 50 | | | |
| MIT, Cambridge [589-596] | 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 [78]. 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 | | Power [MW] | Efficiency [%] | Pulse length [s] |
|---|--------------------|--------------|------------|---------------|-------------------|---------------------|
| | | cavity | output | | | |
| KIT ¹⁾ , Karlsruhe [77,526-539,541-543] | 136.3 | $TE_{26,14}$ | TEM_{00} | 1.02 | 23.5 | 0.001 |
| | 138.7 | $TE_{27,14}$ | TEM_{00} | 1.14 | 26.1 | 0.001 |
| | 140.8 | $TE_{28,14}$ | TEM_{00} | 0.92 | 24.0 | 0.001 |
| | 142.2 | $TE_{26,15}$ | TEM_{00} | 0.90 | 20.6 | 0.001 |
| | 144.4 | $TE_{27,15}$ | TEM_{00} | 0.96 | 23.1 | 0.001 |
| | 146.7 | $TE_{28,15}$ | TEM_{00} | 1.13 | 25.6 | 0.001 |
| | 149.0 | $TE_{29,15}$ | TEM_{00} | 1.08 | 22.9 | 0.001 |
| | 151.1 | $TE_{30,15}$ | TEM_{00} | 1.00 | 21.3 | 0.001 |
| | 152.4 | $TE_{28,16}$ | TEM_{00} | 0.75 | 20.8 | 0.001 |
| | 154.6 | $TE_{29,16}$ | TEM_{00} | 0.94 | 23.4 | 0.001 |
| | 156.9 | $TE_{30,16}$ | TEM_{00} | 1.24 | 25.4 | 0.001 |
| | 159.2 | $TE_{31,16}$ | TEM_{00} | 1.04 | 23.9 | 0.001 |
| | 160.7 | $TE_{29,17}$ | TEM_{00} | 0.99 | 20.7 | 0.001 |
| | 162.8 | $TE_{30,17}$ | TEM_{00} | 0.98 | 20.7 | 0.001 |
| | 165.1 | $TE_{31,17}$ | TEM_{00} | 1.24 | 26.3 | 0.001 |
| EGYC ²⁾ [567-570] | | | | 1.24 | 41 (SDC) | 0.001 |
| | 167.2 | $TE_{32,17}$ | TEM_{00} | 1.22 | 25.6 | 0.001 |
| | 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 [578-581]. 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 [543].

| 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 | NIFS/TOHOKU/TOSHIBA |
| | | 0.3 | 77 | 900 | NIFS/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 |
| | | 1200 | 170 | 100 | CYCOM |
| | | 1000 | 170 | 570 | GYCOM |
| | | 900 | 170 | 1000 | 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 (**) HE₁₁ mode, respectively.

Tab. IX: Experimental parameters of high-power millimeter-wave vacuum windows [14,18,19,21,60,83-89,215,216,274-287,291,297,301,302,324-326,332-413, 431-463,465-532,588,597-643].

| Material | BeO p.c. | BN (CVD) p.c. | Si ₃ N ₄ composite (SN-287) | Sapphire (Al ₂ O 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/cm ³] | 2.85 | 2.3 | 3.4 | 4.0 | 2.3 | 3.515 | 3.2 |
| Specific Heat Capacity c_p [J/g K] | 1.05 | 0.8 | 0.6 | 0.8 | 0.7 | 0.502 | 0.38 |
| Young's Modulus E [GPa] | 345 | 70 | 320 | 385 | 190 | 1050 | 700 |
| Therm. Expans. Coeff. α [10 ⁻⁶ /K] | 7.2 | 3 | 2.4 | 5.5 | 2.5 | 1.0 | 4.3 |
| Permittivity (145 GHz) ϵ_r' | 6.7 | 4.7 | 7.84 | 9.4 | 11.7 | 5.67 | 9.92 |
| Loss Tangent (145 GHz) $\tan\delta$ [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 \varnothing [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 $P_T = R'\rho c_p/((1+\epsilon_r')\tan\delta)$ | 0.06 | 0.05 | 0.36 | 0.09 | 106 | 118 | 0.63 |
| Radiation Sensitivity n(10 ²⁰ -10 ²¹ n/m ²) 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) [60,66,618,644-647].

| Material | Sapphire (Al ₂ O 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/cm ³] | 4.0 | 2.3 | 3.52 |
| Specific Heat Capacity c_p [J/g K] | 0.8 | 0.7 | 0.52 |
| Young's Modulus E [GPa] | 402 (405) | 190 | 1050 |
| Therm. Expans. Coeff. α [10 ⁻⁶ /K] | 5.5 | 2.5 | 1.2 |
| Permittivity (145 GHz) ϵ_r' | 9.3 | 11.5 | 5.67 |
| Loss Tangent (145 GHz) $\tan\delta$ [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 \varnothing [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 $P_T = R'\rho c_p/((1+\epsilon_r')\tan\delta)$ | 71 (4460) | 907 | 490 |
| Radiation Sensitivity $n(0.3 \cdot 10^{21}n/m^2)$ 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 LN₂-temperature – 77 K (LNe-Temperature – 30 K) (p.c. = poly-crystalline, s.c. = single-crystalline) [618].

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 [58-62,66,618]. 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

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

and

$$P_T = R' \rho \cdot c_p \cdot ((1 + \epsilon'_r) \tan \delta). \quad (8)$$

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, Si₃N₄ 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 LN₂-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 LN₂-edge-cooled sapphire window of the 118 GHz TED gyrotron (0.5 MW, 210 s) [399-409] operates close to the allowable lower limits of R' and P_T . However, the mechanical features and the required cooling auxiliaries 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 [606].

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 [58-62,66,618]. 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) $\tan \delta = 2.5 \cdot 10^{-4}$, $k = 40$ W/mK |
| ② | Diamond | single-disk | Gaussian | circular ($\varnothing = 80$ 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 ($\varnothing = 80$ 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 ($\varnothing = 80$ 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 ($\varnothing = 80$ 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 [58-62,66,618].

7 Harmonic and Very High Frequency Gyrotron Oscillators

| Institution | Frequency [GHz] | Mode | Power [kW] | Efficiency [%] | Pulse length [ms] |
|-------------------------------------|--------------------|--|------------|----------------|-------------------|
| CPI ¹⁾ , Palo Alto [648] | 250 | TE _{11,1} /TE _{11,2} | 10 | 3.4 | 0.1 |
| IAP, N. Novgorod [96,97,649] | 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 [650,651] | 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 [652] | 423 | TE ₂₆ | 4.4 | 2.8 | 0.004 |
| UNIVERSITY, Fukui [106-119,653-665] | 350.3 | TE ₆₅ | 52 | 8.3 | 0.003 |
| | 384 ^{*)} | TE ₂₆ | 3 | 3.7 | 1 |
| | 388.2 | TE ₁₈ | 62 | 158.0 | 0.003 |
| | 392.6 | TE ₈₅ | 60 | 9.6 | 0.004 |
| | 402 ^{*)} | TE ₅₅ | 2 | 3 | 1 |
| | 576 ^{*)} | TE ₂₆ | 1 | 2.5 | 0.5 |
| | 874 ^{*)} | TE ₁₉ | 0.6 | 2.0 | 0.5 |

¹⁾ Communications & Power Industries; formerly VARIAN ^{*)} In collaboration with TOSHIBA, Ottawara

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 [666-671] | 89.3 | TE ₃₁ | 3 | 1.7 | 3.3 | 1 |
| | 112.7 | TE ₄₁ | 4 | 0.47 | 1 | 1 |
| | 138.0 | TE ₅₁ | 5 | 0.1 | 0.2 | 1 |
| IAP, N. Novgorod [102-105,672] | 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 [μ s] | |
|---|--------------------|---------------------|---------------|-------------------|-------------------------------|-------------------------|
| IAP, Nizhny Novgorod [96-102,104,105] | 250 | TE _{20,2} | 0.3 | 31 | 30 - 80 | |
| | 304 | TE _{22,8} | 0.3 | 25% | 25 | |
| | 330 | | 0.13 | 17 | 30 - 80 | |
| | 430 | | 0.12 | 8 | 30 - 80 | |
| | 500 | TE _{28,3} | 0.1 | 8.2 | 30 - 80 | |
| | 540 | | 0.06 | 6 | 30 - 80 | |
| | 600 | TE _{38,2} | 0.053 | 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 | |
| MIT, Cambridge [68,583,589-596, 673-684] | 1300 | TE _{24,4} | 0.0005 | 0.6 | 40 | |
| | 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 [685] | 216 | TE ₂₃ | 0.02 | 14.0 | 4 | |
| | 221 | TE ₀₃ | 0.02 | 8.5 | 4 | |
| UNIVERSITY, Fukui [654,655] | 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, 1 ms) [106-156,649-693].

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 TE₀₁ mode near the fundamental cyclotron frequency at 95 GHz, the output cavity operated at the 3rd harmonic 285 GHz in the TE₀₃ mode [694-698]. 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 [699,700].

| Institution | Frequency [GHz] | Mode | Voltage [kV] | Current [A] | Power [MW] | Efficiency [%] | |
|----------------------|-----------------|--------------------|--------------|-------------|------------|----------------|----|
| MIT, Cambridge [674] | 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 [674]) operating at the fundamental electron cyclotron resonance frequency (pulse length 1.5 μ s).

| Institution | Frequency [GHz] | Mode | Voltage [kV] | Current [A] | Power [MW] | Efficiency [%] |
|----------------------|-----------------|---------------------|--------------|-------------|------------|----------------|
| MIT, Cambridge [674] | 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 [674]) operating at the fundamental electron cyclotron resonance frequency (pulse length 1.5 μ s).

8 Gyrotrons for Technological Applications

| Institution | Frequency [GHz] | Mode cavity | Mode output | Power [kW] | Efficiency [%] | Voltage [kV] | Magnet |
|--|------------------------------|------------------------------------|------------------------------------|------------------|----------------|--------------|------------------------------------|
| CPI¹⁾, Palo Alto [13,18,648] | 28 | TE ₀₂ | TE ₀₂ | 15 | 38 | 40 | roomtemp. |
| | 28 (2Ω _c) | TE ₀₂ | TE ₀₂ | 10.8 | 33.6 | 30 | roomtemp. |
| | 60 | TE ₀₂ | TE ₀₂ | 30 | 38 | 40 | cryo. mag. |
| CPI, NIFS [54-56,288-291] Palo Alto, Toki | 84 | TE _{15,3} | TEM ₀₀ | 50 | 14 | 80 | cryo. mag. |
| GYCOM/IAP Nizhny Novgorod, [1,14,71,85,162-166, 169,172-175,177-182, 294,464,465,649,701-713] | 13(15) | TE ₀₁ | TE ₀₁ | 0.3(4) | 20(50) | 25(15) | roomtemp. |
| | 24.1 (2Ω _c) | TE ₁₁ | TE ₁₁ | 3.5 | 23 | 12 | roomtemp. |
| | 24.1 (2Ω _c) | TE ₋₂₁ | TE ₁₁ | 3.4 | 23 | 15 | PM, 116kg |
| | 24.1 | TE ₃₂ | TE ₃₂ | 36 | 50 | 33 | roomtemp. |
| | 24.1 (2Ω _c) | TE ₁₂ | TE ₁₂ | 13 | 50 | 25 | roomtemp. |
| | | | | 28 | 32 | 25 | roomtemp. |
| | | | | 6.5 | 60 (SDC) | 17.5 | roomtemp. |
| | 28/30 (2Ω _c) | TE ₀₂ | TE ₀₂ | 10 | 42 | 26 | roomtemp. |
| | | | | 30 | 35 | 26 | roomtemp. |
| | 28.1/28.7 (2Ω _c) | TE ₂₃ /TE ₀₃ | TE ₂₃ /TE ₀₃ | 10 | 20 | 23-24 | 2 kHz frequency switching |
| | 28.25 (2Ω _c) | TE ₁₂ | TE ₁₂ | 12 | 20 | 25 | PM, 68 kg ²⁾ |
| | 31.8-34.8 | TE ₁₁ | TE ₁₁ | 1.2 | 40 | 12 | mech. tun. |
| | 35.5-37.5 | TE ₀₁ | TE ₀₁ | 0.5 | 15.3 | 16 | mech. tun. |
| | 35.15 | TE ₀₂ | TE ₀₂ | 9.7 | 43 | 25 | cryo. mag. |
| | 35 | TE ₀₂ | TEM ₀₀ | 10-50 | 30-40 | 25-30 | cryo. mag. |
| | 37.5 | TE ₆₂ | TEM ₀₀ | 20 | 35 | 30 | cryo. mag. |
| | 68-72 | TE ₁₃ | TE ₁₃ | 1.4 | 22 | 17.5 | mech. tun. |
| | 83 | TE ₉₃ | TEM ₀₀ | 10-50 | 30-40 | 25-30 | cryo. mag. |
| | 150 | TE ₀₃ | TE ₀₃ | 22 | 30 | 40 | cryo. mag. |
| | 157 (2Ω _c) | TE ₀₃ | TE ₀₃ | 2.4 | 9.5 | 18 | cryo. mag. |
| 191.5 (2Ω _c) | | | 0.55 | 6.2 | 22 | cryo. mag. | |
| 250 (2Ω _c) | TE ₀₂ | TE ₀₂ | 4.3 | 18 | 20 | cryo. mag. | |
| 250 (2Ω _c) | TE ₆₅ | TE ₆₅ | 1 | 5 | 20 | cryo. mag. | |
| 326 (2Ω _c) | TE ₂₃ | TE ₂₃ | 1.5 | 6 | 20 | cryo. mag. | |
| MICRAMICS, San Jose [714] | 24.1 (2Ω _c) | TE ₂₂ | TEM _{mixed} | 5 | 25 | 23 | roomtemp. |
| | | | TE ₂₂ | 10 | 25 | 23 | roomtemp. |
| MITSUBISHI, Amagasaki [176,715-717] | 28 (2Ω _c) | TE ₀₂ | TE ₀₂ | 10 | 38.7 | 21 | PM, 600 kg ²⁾ tapered B |
| UESTC, Chengdu [718] | 37.5 | TE ₁₃ | TE ₁₃ | 57 (0.4 average) | 9 | 50.5 | roomtemp. |
| UNIV. Fukui, IAP Nizhny Novgorod/ GYCOM [168,719-726] | 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) [169,172,173]. 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 [727-734] | 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 Lebedev/General Phys. Inst. Moscow [728,735-737] | 10 | TE ₁₃ | 0.3 | 0.4 | 25 | 20 | slotted cavity |
| | 10 | TE ₁₃ | 0.3 | 1.0 | 60 | 15 | plasma-filled |
| | 40 | TE ₁₃ | 0.4 | 1.3 | 25 | 5 | slotted cavity |
| KIPT, Kharkov [738] | 12 | TE ₁₃ | 0.12 | 8.0 | 60 | 6.3 | plasma filled slotted cavity |
| UNIV. Michigan [739-745] | 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 |
| | 10 | TE ₁₁ | | | 40 | | unslotted cavity |
| | | | | | 20 | | unsl. noncoax. cavity |
| | | 0.4 | 0.025 | 0.6 | 6 | | |
| NRL, Washington D.C. [746-749] | 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. [750] | 3.1 | | 0.75 | 8.0 (30) | 1800 | 8 | also vircator interaction |
| UNIV. Niigata [751] | 18.2 | TE ₀₁ | 0.08 | 0.5 | 0.2 | 0.55 | |
| UNIV. Strathclyde [752-757] | 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 [238,697,758-766] | 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 ($\tau = 10$ ns) and the 115, 130, 223, 369, 371, 414 and 469 GHz experiments employed a quasi-Pierce type thermionic gun with kicker ($\tau = 10$ μ s, 1 Hz).

10 Quasi-Optical Gyrotrons

| Institution | Frequency [GHz] | Mode resonator | Power [kW] | Efficiency [%] | Pulse length [ms] | Type |
|------------------------------------|---------------------|----------------------------------|------------|----------------|-------------------|------------------|
| ABB, Baden [215,271] | 92 | TEM _{00q} | 90 | 10 | 10 | |
| CRPP, Lausanne [67,68,215,767] | 90.8 | TEM _{00q} | 150 | 15 | 5 | |
| | 100 | TEM _{00q} | 90 | 15 | 15 | |
| | 200 (2 Ω_c) | TEM _{00q} | 8 | 3.5 | 15 | |
| IAP, Nizhny Novgorod [768] | 100 | TE ₀₆₁ | 260 | 6.5 | 0.04 | echelette cavity |
| MIT, Cambridge [769,770] | 136 | HE ₀₆₁ ⁽⁰⁾ | 83 | 18 | 0.003 | confocal |
| | 114.3 | HE ₀₅₁ ⁽⁰⁾ | 75 | 16 | 0.003 | slot-cavity |
| Moscow-State UNIV. [771] | 35 | TEM _{00q} | 1 | 15 | CW | |
| | 95 | TEM _{00q} | 1 | 15 | CW | |
| NRL, Washington D.C. [587,772,773] | 110 | TEM _{00q} | 80 | 8 | 0.013 | |
| | | | 600 | 9 | 0.013 | |
| | | | 431 | 12.7 (SDC) | 0.013 | |
| | 120 | TEM _{00q} | 197 | 16.1 (SDC) | 0.013 | |
| | | | 600 | 9 | 0.013 | |
| | | | 200 | 12 | 0.013 | |
| TOSHIBA, Otawara [321] | 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 (2Ω _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 (2Ω _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 [758,759,774-783] | 125 | TE ₄₁ | 10 | 2 | - | 0.9 | 0.5 | 1.0 | oscillator |
| LLNL Livermore [784] | 220 | TE ₁₁ | 50 | 2.5 | - | 3.0 | 2.0 | 1.0 | oscillator |
| MIT Cambridge [226,785,786] | 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 [787,788] | 15 | TE ₁₁ | 7 | 1.5 | - | 0.45 | 0.4 | 1.2 | oscillator |
| UNIV. Strathclyde [789-791] | 13 | TE ₁₁ | | | - | 0.3 | 0.4 | 0.04 | oscillator |
| | 14.3 (2Ω _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 [227] | 9.5 | TM ₀₁ | 35 | 3.5 | - | 1.15 | 0.4 | 2.5 | oscillator corr.w.g. |
| Tomsk Polytechn. Inst. [228] | 25 | | 20 | 0.2 | - | 0.64 | 0.9 | 14 | oscillator diel.w.g. |
| UNIV. Niigata, NIFS, UNIV. Maryland [229] | 19.5 | TM ₀₁ | 0.2 | 3.8 | - | 0.9 | 0.035 | 0.15 | oscillator corr.w.g. |
| UNIV. Yale, NRL, Washington D.C. [230] | 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 [18,212] | 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. [192,345,792-799] | 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 [800,801] | 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 | |
| IAP Nizhny Novgorod [802-814] | 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(230) | 22(30) | | 0.3 | 2-cav. Gyrotron |
| | 93.2 | TE ₀₁ | 4 | 65 | 26 | 35 | 0.3 | max. power |
| | | | 4 | 57 | 34 | 40 | 0.3 | max. efficiency |
| | 93.5 | TE ₀₂ | 2 | 140 | 18 | 18 | 0.35 | |
| | | | 2 | 207 | 30 | 21 | 0.2 | shaped B |
| | 93.2 | TE ₀₂ | 3 | 340 | 24.5 | 23 | 0.3 | shaped B |
| IECAS, Beijing [815,816] | 35 ($2\Omega_c$) | TE ₀₂ | 3 | 212 | 16 | 24 | 0.44 | |
| Kwangwoon Univ., Seoul [817] | 27.85 | TE ₀₁ | 5 | 150 | 26 | 50 | 0.1 | |
| NRL, Washington D.C. [189-192,212,587, 818-829] | 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 [830] | 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. [189-193,277,794-799] | 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 [804] | 9.17 | TE ₁₁ | 2 | 0.7 | 70 | 22 | 0.3 | |
| IAP/ISTOK Moscow [805,808] | 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 gyrokystron experimental results.

| Institution | Frequency [GHz] | Mode output | No. of cavities | Power [MW] | Efficiency [%] | Gain [dB] | BW [%] | Type |
|--|--------------------------|-------------------|--|---------------|-------------------|--------------|-----------|-----------------|
| IAP, Nizhny Novgorod [831-836] | 30 | TE _{5,3} | 2 (TE _{5,2} /TE _{5,3}) | 15 | 40 | 30 | 0.14 | triode gun |
| | | TE _{3,2} | 3 (TE _{5,2} /TE _{5,2} /TE _{5,3}) | 12 | 30 | 38 | 0.14 | |
| UNIV. Maryland [183-187,837-849] | 8.57 | TE ₀₁ | 3 | 75 | 32 | 30 | 0.2 | coaxial |
| | | 9.875 | TE ₀₁ | 2 | 24 | 30 | 33 | 0.2 |
| | 9.87 | TE ₀₁ | 3 | 27 | 32 | 36 | 0.2 | max. power |
| | | | 3 | 16 | 37 | 33 | 0.2 | max. efficiency |
| | | | 3 | 20 | 28 | 50 | 0.2 | max. gain |
| | 17.14 (2Ω _C) | TE ₀₂ | 3 | 27 | 13 | 25 | 0.1 | coaxial |
| | 19.76 (2Ω _C) | TE ₀₂ | 4 | 18.5 | 7.0 | 23.3 | 0.35 | coaxial |
| | | | 2 | 32 | 29 | 27 | 0.1 | |
| 29.57 (3Ω _C) | TE ₀₃ | 2 | 1.8 | 2.0 | 14 | 0.1 | | |

Table XXIV: Relativistic pulse gyrokystron experimental results.

| Institution | Frequency [GHz] | Mode | Power [kW] | Efficiency [%] | Gain [dB] | Bandwidth [%] | Type |
|--|-------------------------|--------------------------------------|---------------|-------------------|--------------|------------------|---|
| BVERI, Beijing [850-852] | 35.3 | TE ₀₁ | 156 | 23.3 | 44 | 5.2 | Periodic SiC loading |
| CPI¹⁾, Palo Alto [18,172,212,345,799, 853-856] | 5.18 | TE ₁₁ | 120 | 26 | 20 | 7.3 | MIG |
| | 5.2 | TE ₁₁ | 64 | 14 | 17.5 | 7.3 | Pierce-helix gun |
| | 93.7 | TE ₁₁ | 28 | 7.8 | 31 | 2 | Pierce-helix gun |
| | 95 | TE ₀₁ | 1.5 (0.6 av.) | 4.2 | 42 | 7.7 | |
| E2V, Chelmsford [857] | 10 | TE ₋₂₁ /TE ₊₁₁ | 180 | | | | gridded gun |
| IAP, Nizhny Novgorod [858-866] | 36.3 | TE ₋₂₁ /TE ₊₁₁ | 180 | 27 | 25 | 10 | cusplike gun with axis-encircl. beam |
| | | | 120 | 23 | 20 | 6 | shortpulse 3 μs |
| | 30.5 | TE ₋₂₁ /TE ₊₁₁ | 3 | 6.5 | 33 | 3.5 | longpulse 110 μs |
| MIT, Cambridge [867-876] | 140 | HE ₀₆₁ ⁰ | 30 | 12 | 29 | 1.6 | CW operation |
| | | | | | | | quasi-optical at 1 kW 400 ps modulation pulse |
| NRL, Washington D.C. [212,877-883] | 32.5 | TE ₁₀ | 6.3 | 10 | 16.7 | 33 | 1-stage tapered |
| | 35.5 | TE ₁₀ | 8 | 16 | 25 | 20 | 2-stage tapered |
| | 32.3 | TE ₁₀ | 50 | 28 | 25 | 11 | folded waveguide |
| | 34.0 | TE ₀₁ | 137 | 17 | 47 | 3.3 | axis-encircl. beam |
| | 35.6 | TE ₁₁ | 70 | 17 | 60 | 17 | 2-stage output |
| UC Los Angeles/Davis [884-896] | 9.3 | TE ₁₀ | 55 | 11 | 27 | 11 | diel. coat. waveg. |
| | 10.4 (3Ω _C) | TE ₃₁ | 6 | 5 | 11 | 3 | axis-encircl. beam |
| | 15.7 (2Ω _C) | TE ₂₁ | 207 | 12.9 | 16 | 2.1 | slotted waveg. |
| | 16.2 (8Ω _C) | TE ₈₁ | 0.5 | 1.3 | 10 | 4.3 | axis-encircl. beam |
| | 92 | TE ₀₁ | 140 | 22 | 60 | 2.2 | heavily loaded + short copper stage |
| NTHU, Hsinchu [232-234,897-903] | 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 [904,905] | 34 | TE ₀₁ | 160 | 22.8 | 40 | 5 | lossy circuit |
| UNIV. Tel Aviv [906] | 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 [235,858-860,907-911] | 9.4 ($2\Omega_C$) | TE ₋₂₁ /TE ₊₁₁ | 1.1 | 29 | 37 | 21 | helical waveguide with $\Delta m=3$ perturb. Axis encircl. E-beam |
| | 36.5 ($2\Omega_C$) | TE ₋₂₁ /TE ₊₁₁ | 3.0 | 27 | 33 | 20(ΔB) | see above |
| MIT, Cambridge [912] | 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. *) [913,914] | 35 | TE ₁₁ | 20 | 11 | 30 | | explosive-emission gun, bifilar helical wiggler |
| UNIV. Strathclyde [915-920] | 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 | TW section | Power [kW] | Efficiency [%] | Gain [dB] | BW [%] |
|---|-----------------|-------------------------------------|------------------|--------------|----------------|-----------|--------|
| CPI ¹⁾ , Palo Alto [190,192,277,799] | 94 | TE ₀₁ (4 cav.) | TE ₀₁ | 59 (5.9 av.) | 14.9 | 35 | 1.6 |
| NRL, Washington D.C. [921] | 4.5 | TE ₁₀ | TE ₁₀ | 73 | 22.5 | 37 | 1.5 |
| | 31.5 | TE ₄₂ (2Ω _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. [922,923] | 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 | TW section | Power [kW] | Efficiency [%] | Gain [dB] | BW [%] |
|--|-----------------|---|-------------------------------------|------------------|----------------------|-------------|--------|
| IECAS [924-931] | 33.1 | TE ₀₁ /coupled cavity (2Ω _c) | TE ₀₃ (Ω _c) | 75 | 7.1 | 25 | 1.1 |
| Seoul National UNIV. [932] | 33.9 | TE ₁₀ | TE ₁₀ (3Ω _c) | 10 ⁻⁴ | 2 · 10 ⁻³ | LO-gyro-TWT | 3.8 |
| UNIV. Maryland. [237,933-938] | 31.8 | TE ₂₂ | TE ₄₂ (2Ω _c) | 100 | 20 | 30 | 1.3 |
| | 33.7 | TE ₀₂ | TE ₀₃ (2Ω _c) | 430 | 35 | 30 | 0.3 |
| | 34.6 | TE ₀₂ | TE ₀₃ (2Ω _c) | 180 | 32 | 30 | 3.0 |
| | 32.5 | TE ₀₂ | TE ₀₃ (2Ω _c) | 200 | 12 | 36 | 3.0 |
| | 35 | TE ₀₂ /TE ₀₃ (2Ω _c) buncher | TE ₀₄ (2Ω _c) | 110 | 32 | 53 | 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 | TW section | Power [MW] | Efficiency [%] | Gain [dB] | BW [%] |
|----------------------|-----------------|----------------------------|-------------------------------------|------------|----------------|-----------|--------|
| UNIV. Maryland [939] | 9.878 | TE ₀₁ | TE ₀₁ | 21.6 | 21 | 25.5 | |
| | 19.76 | TE ₀₁ (9.88GHz) | TE ₀₂ (2Ω _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 [940-943] | 8.6 | TE ₊₂₁ /TE ₋₁₁ | 65 | 16.5 | 17 | quasi-Pierce gun with kicker |
| IAP, N. Novgorod KIT ¹⁾ , Karlsruhe [169,708,860-866, 944,945] | 24.7 | TE ₊₂₁ /TE ₋₁₁ | 7 | 15 23 (SDC) | 5 | MIG CW operation |
| IAP, Nizhny Novgorod [859] | 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 [946,947] | 17.2 | TE ₀₁ | 48 | 10.5 21(SDC) | 5 | TE ₁₀ ^r output |
| MIT, Cambridge, LLNL, Livermore [948] | 140 | TE ₁₂ ^c | 2 | 2 | 9 | |
| NRL, Washington D.C. [949] | 27.8 | TE ₁₀ ^r | 2 | 9 | 3 | electr. tuning |
| | 29.2 | TE ₁₀ ^r | 6 | 15 | 13 | magn. tuning |
| NTHU, Hsinchu [950-958] | 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 [959-961] | 96 | TE ₊₂₁ /TE ₋₁₁ | 5 | 8 | 10 | |
| UNIV. Utah [962] | 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 μ s)

| Institution | Frequency [GHz] | Mode | Power [MW] | Efficiency [%] | BW [%] | Voltage [MV] | Current [kA] | Type |
|--|-------------------|---------------------------------------|------------|----------------|----------------------------|----------------|--------------|--------------------------------------|
| IAP, N. Novgorod [963,964] | 10 | TM ₁₁ | 200 | 22 | | 0.45 | 2 | Cherenkov with cycl. mode selection |
| | 35(2 Ω c) | TE ₋₂₁ / TE ₊₁₁ | 1.15 | 10 axis | 15(Δ B) encirl. | 0.35 e-beam | 0.032 | hel. w.g. with $\Delta m=3$ perturb. |
| UNIV. Kanazawa [965,966] | 9-13 | TE ₁₀ ^r | 1 | 0.75 (0.02) | 1 | 0.45 | 0.3(10) | |
| UNIV. Michigan [967,968] | 4-6 | TE ₁₁ | 55(30) | 8(4.3) | 1 | 0.7 | 1 | |
| | 5-6(2 Ω c) | TE ₁₁ | 1 | 0.15 | 4 | | | |
| USAF Phillips Lab. Aberdeen [969,970] | 4.2 | TE ₂₁ | 4 | 1 | 1 | 0.4 | 1 | |
| | 4.4 | TE ₀₁ | 0.15 | 0.04 | 1 | 0.4 | 1 | |

r = rectangular waveguide

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 [971] | 34.1 ($2\Omega_c$) | TE_{11}^c | 4x TE_{10}^r | 88 | 36 | 0.02 | cusp gun |
| UNIV. Tohoku, Sendai [972-980] | 10.0 | TE_{11}^r | TE_{11}^r | 10 | 36 | 0.02 | magnetron-type cavity |
| | 10.5 ($2\Omega_c$) | TE_{31}^c | TE_{31}^c | 0.7 | 10 | | |
| | | | | 1.3 | 7 | | |
| | 30.3 ($3\Omega_c$) | TE_{41}^c | TE_{01}^c | 6.9 | 35 (75 electr.) | | |
| | | | 6.9 | 44(SDC) (92 electr.) | | | |
| | 100 ($10\Omega_c$) | $TE_{11,1}^c$ | TE_{01}^c | 0.32 | 1.7 (5 electr.) | | auto-res. |
| | 10 | TE_{21}^c | TE_{21}^c | 1.5 | 25 | | |

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

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 [981] | | | | | |

Table XXX: Experimental results of gyropeniotrons.

| Institution | Frequency [GHz] | No. of Cavities | Voltage [MW] | Current [A] | Power [MW] | Efficiency [%] | Gain [dB] | Pulse length [μ s] |
|-------------------------------------|------------------------|-----------------|--------------|-------------|------------|----------------|-----------|-------------------------|
| BINP, Novosibirsk [240,241,982-984] | 0.915 | 3 | 0.3 | 12 | 2.6 | 73 | 30 | 30 |
| | 7.01 ($2\Omega_c$) | 5 | 0.427 | 230 | 55 | 56 | 72 | 1.1 |
| NRL, Washington D.C. [985-990] | 11.424 ($2\Omega_c$) | 7 | 0.48 | 210 | 25 | 25 | 59 | 0.2 |
| | | | | | 12 | 12 | 59 | 1.2 |
| NRL, Yale UNIV. / Omega-P [990-994] | 34.3 ($3\Omega_c$) | 7 | 0.455 | 187 | 17 | 19.5 | 47 | 0.1 |
| | | | | | 26 | 27 | 57 | 0.0005 |

BINP: Budker Institute of Nuclear Physics

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 [995-1005] | 3 | 0.11 | 120 | TE ₁₁ ^c | 40 | 2.3 | | 2.2 | 0.8 | Ind. LINAC | 0.025 | spn.emiss. |
| | 8.6 | 0.45 | 20 | TEM ₀₀ (2 nd 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 [1006-1008] | 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 [1009] | 100 | 0.1 | 20 | TE ₀₂ ^c | 1 | 2 | | 0.5 | 0.15 | Pulse Line | 0.03 | spn.emiss. |
| ENEA Frascati [1010-1014] | 85-150 | 0.61 | 25 | TE ₀₁ ^r | 0.0015 | 0.19 | | 2.3 | 0.00035 | Microtron | 5.5 | oscillator |
| EP Palaiseau [1015] | 120 | 0.03 | 20 | TE ₁₁ ^c | 11.5 | 6.4 | | 0.6 | 0.3 | Electrostatic | 0.02 | superrad. |
| FOM Nieuwegein [247-257,1016] | 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 |
| | 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 Microwave Lab. Palo Alto [245] | 2.6 | 0.04 | 74.2 | TE ₀₁ ^r | 1.2 | 10 | 6 | 0.17 | 0.07 | Modulator | 5.0 | amplifier |
| Palo Alto [245] | 2.6-3.7 | 0.04 | 74.2 | TE ₀₁ ^r | 0.9 | 9.2 | 10 | 0.135 | 0.07 | Modulator | 5.0 | amplifier |
| | 15.7 | 0.2 | 23.6 | TE ₀₁ ^c | 1.65 | 6 | 6 | 0.23 | 0.125 | Modulator | 5.0 | amplifier |
| IEE,China [258] | 54 | 0.2 | 3.18 | TE ₀₁ ^c | 0.15 | 6 | 10(30) | 0.07 | 0.037 | Modulator | 4.0 | amplifier |
| | 35 | 0.31 | 110 | | 140 | 5.2 | 57 | 3.4 | 0.95 | Ind. LINAC | 0.05 | amplifier |
| IAP, Nizhny Novgorod [1017-1019] | 16.7 | 0.02 | | TE ₀₁ ^c | 300 | 11 | | 0.6 | 4.5 | Electrostatic | 0.03 | oscillator |
| | 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⁾ [1020-1040] | 75 | 0.10 | 40 | TEM | 100 | 4.2 | | 0.8 | 3.0 | Pulse Line | 1.0 | oscillator |
| IAP/U. Strath./HERC [1041-1043] | 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. [1044-1056] | 29.3 | 0.11 | 60 | TE ₁₁ ^c | 6 | 5(4) | | 0.8 | 0.15(0.2) | Ind. LINAC | 0.2 | oscillator |
| | 30 | 0.12 | 60 | TE ₁₁ ^c | 20 (30) | 20(15) | | 0.8 | 0.13 | Ind. LINAC | 0.2 (0.1) | oscillator |
| | 30.2 | 0.12 | 60 | TM ₁₂ ^c /TE ₁₁ ^c | 15 | 15(10) | | 0.8 | 0.15(0.2) | Ind. LINAC | 0.2 | oscillator |
| | 35 | 0.19 | 72 | TE ₁₁ ^c | 30 | 10 | | 1.5 | 0.2 | Ind. LINAC | 0.2 | amplifier |
| | 250 | 0.05 | 30 | TE ₁₁ ^c | 0.6 | 0.5 | 110 | 0.6 | 0.2 | Ind. LINAC | 0.04 | amplifier |
| ILT/ILE Osaka [1058] | 60-110 | 0.71 | 60 | TE ₀₁ ^r | 0.01 | 0.2 | | 9.0 | 0.05 | RF LINAC | 4x10 ⁻⁶ | oscillator |
| ISAS, Sagamihara [1059] | 11.8 | 0.09 | 32.7 | TM ₈₁ ^c | 3 | 1 | | 0.43 | 0.19 | Pulse Line | 0.4 | oscillator |
| JAEA ²⁾ , Ibaraki [1060,1061] | 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 [1062-1064] | 27 | 0.13 | 32 | TM ₁₁ ^c | 0.001 | 0.15 | | 0.4 | 0.0017 | Electrostatic | 10-30 | oscillator |
| KEK, Tsukuba [1065-1069] | 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 [1070] | 11.2/16.4 | | | TM _{02,03} | 5 | 0.125 | | 0.8 | 5.0 | Modulator | 1.0 | oscil./amp. |
| LLNL, Livermore [199,1071-1076] | 34.6 | 0.37 | 98 | TE ₀₁ ^r | 1000 | 34(7.2) | 52 | 3.5 | 0.85(4.0) | Ind. LINAC | 0.02 | amplifier |
| | 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 | B _w | λ _w | Mode | Power | Efficiency | Gain | Voltage | Current | Accelerator | Pulse-Length | Type |
|---|-----------|----------------|----------------|--|--------------------|-------------------|------|---------|----------------------|---------------|--------------|--------------|
| | [GHz] | [T] | [mm] | | [MW] | [%] | [dB] | [MV] | [kA] | | [μs] | |
| MIT, Cambridge [785,1077-1080] | 9.3 | 0.02 | 33 | TE ₁₁ ^c | 0.1 | 10 | 6 | 0.18 | 0.0055 | Electrostatic | 0.02 | amplifier |
| | 27.5 | 0.05 | 30 | TE ₁₁ ^c | 1 | 10.3(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. [1081,1082] | 13.2-16.6 | 0.1 | 25.4 | TE ₁₁ ^c | 4.2 | 18 | 29 | 0.245 | 0.094 | Modulator | 1.2 | amplifier |
| | 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. [258] | 95 | 0.2 | 100 | | 10 | 4 | | 2.5 | 0.1 | Pulse Line | 0.25 | oscillator |
| RI, Moscow [1083] | 6-25 | 0.03 | 48 | TE ₁₁ ^c /TM ₀₁ ^c | 10 | 1.7 | | 0.6 | 1 | Pulse Line | 2 | spon. emiss. |
| SIAE, Chengdu [1084] | 37 | 0.125 | 34.5 | TE ₁₁ ^c | 7.6 | 5.4 | | 0.5 | 0.28 | Electrostatic | 0.015 | oscillator |
| SIOFM, Shanghai [1085,1086] | 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 [1087] | 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 [1088,1089] | 90 | Smith-Purcell | | TEM ₀₀ | 0.03 | 0.03 | | 0.46 | 0.2 | Pulse Line | 0.015 | oscillator |
| UNIV. Liverpool [259] | 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 [1070,1090,1091] | 35 | CHI-wiggl. | 64 | TE ₀₁ ^{coax} | 0.0038 | 0.018 | 5 | 0.0011 | 0.0019 | Electrostatic | 1 | amplifier |
| | 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 [1092-1094] | 120-880 | 0.15 | 71.4 | | 0.027 | 0.5 | | 2-6 | 0.002 | Electrostatic | 1-20 | oscillator |
| UNIV. Strathclyde [1095-1097] | 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⁾ [1098-1112] | 32.5 | 0.13 | 23 | TE ₁₁ ^c | 0.5 | 5.0 | | 0.3 | 0.03 | Pulse Line | 0.1 | oscillator |
| | 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 [1113-1117] | 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 ⁽¹⁾ | 0.01 | 0.7(0.5) | | 1.1-1.5 | 0.001(0.0014) | Electrostatic | 30000 | oscillator |
| UNIV. Twente [1118] | 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 [247-257,1016]. 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) [5,6].

| | 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 | $\Delta U_{\text{beam}} + \Delta U_{\text{mod}}$: fast step tuning (5%) ΔB : slow step tuning (35%) | ΔU_{beam} : fast continuous tuning (10%) slow mechanical tuning (50%) |
| 5. Electron beam | magnetron injection gun | Pierce electron gun, acceleration and deceleration tubes, beam optics |
| 6. Ohmic losses in cavity (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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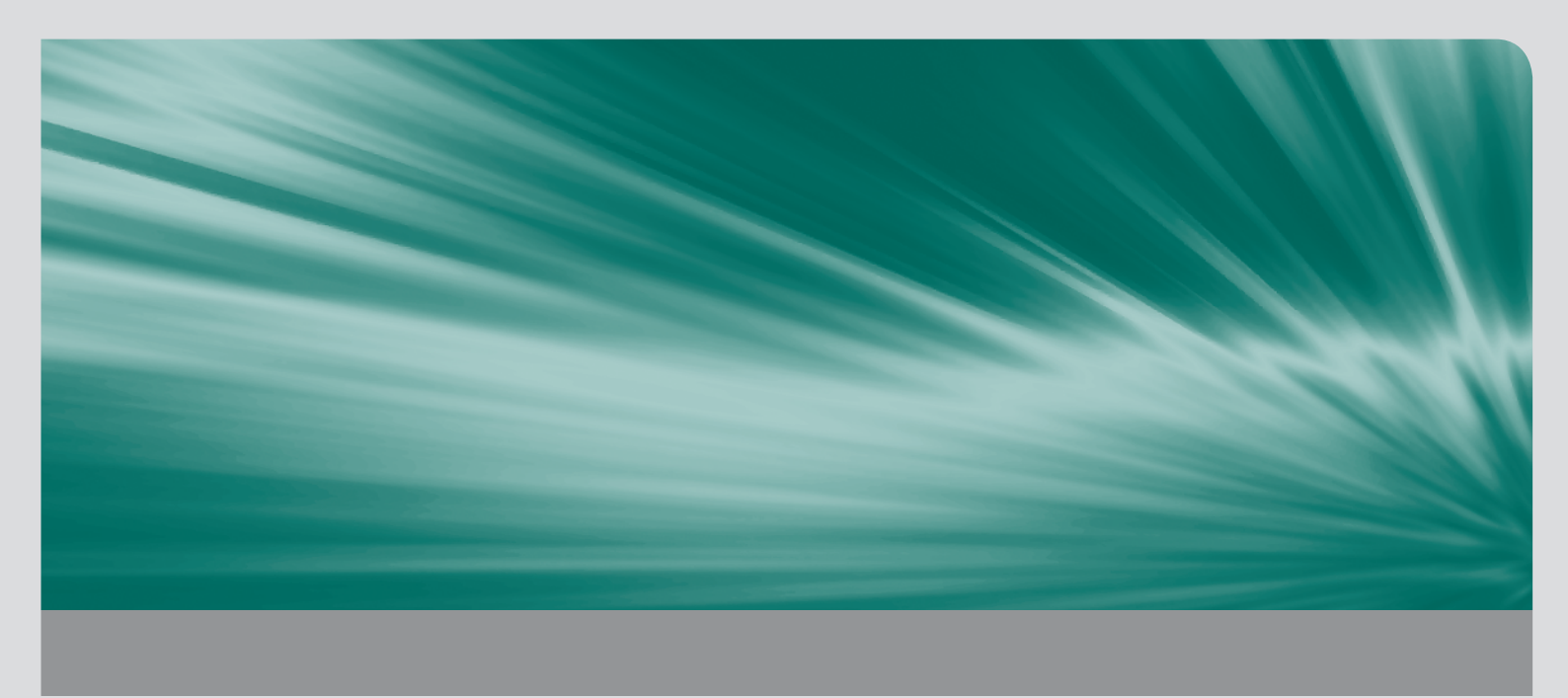
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Gyrotron oscillators are mainly used as high power millimeter wave sources for electron cyclotron resonance heating (ECRH), electron cyclotron current drive (ECCD), stability control and diagnostics of magnetically confined plasmas for generation of 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 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 0.9 MW with a pulse duration of 1000 s and 55% efficiency. The short-pulse preprototype 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 $P_{\text{out}} = 40$ kW with $\tau = 40$ μ s at frequencies up to 650 GHz ($\eta > 4\%$), $P_{\text{out}} = 5.3$ kW at 1 THz ($\eta = 6.1\%$), and $P_{\text{out}} = 0.5$ kW at 1.3 THz ($\eta = 0.6\%$). Gyrotron oscillators have also been successfully used in materials processing. Such technological applications require gyrotrons with the following parameters: $f > 24$ GHz, $P_{\text{out}} = 4$ -50 kW, CW, $\eta > 30\%$. 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.