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**State-of-the-Art of
High Power Gyro-Devices
and Free Electron Masers
Update 2002**

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AND FREE ELECTRON MASERS
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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 1 MW gyrotrons employing synthetic diamond output windows is 5 s at 110 GHz (CPI and JAERI-TOSHIBA), 12 s at 140 GHz (FZK-CRPP-CEA-TED) and 9 s at 170 GHz (JAERI-TOSHIBA), with efficiencies slightly above 30%. Total efficiencies of 45-50 % have been obtained using single-stage depressed collectors (for energy recovery). The energy world record of 160 MJ (0.89 MW at 180 s pulse length and 140 GHz) at power levels higher than 0.8 MW has been achieved by the European FZK-CRPP-CEA-TED collaboration at FZK where the pulse length restriction to 180 s is due to the HV power supply at $I_{\text{beam}} \approx 40$ A. At lower beam current ($I_{\text{beam}} = 26$ A) it was even possible to obtain 506 MJ (0.54 MW for 937 s). The longest shot lasted for 1300 s at 0.26 MW output power. These very long pulses were limited by a pressure increase in the tube. A maximum output power of 1.2 MW in 4.1 s pulses was generated with the JAERI-TOSHIBA 110 GHz gyrotron. The Russian and the Japan 170 GHz ITER gyrotrons achieved 0.5 MW at 80s pulse duration and 0.3 MW at 60s, respectively. Diagnostic gyrotrons deliver $P_{\text{out}} = 40$ kW with $\tau = 40$ μ s at frequencies up to 650 GHz ($\eta \geq 4\%$). Gyrotron oscillators have also been successfully used in materials processing. Such technological applications require gyrotrons with the following parameters: $f \geq 24$ GHz, $P_{\text{out}} = 10$ -50 kW, CW, $\eta \geq 30\%$. This paper gives an update of the experimental achievements related to the development of high power gyrotron oscillators for long pulse or CW operation and pulsed gyrotrons for plasma diagnostics. In addition, this work gives a short overview of the present development status of coaxial cavity gyrotrons, gyrotrons for technological applications, relativistic gyrotrons, quasi-optical gyrotrons, fast- and slow-wave cyclotron autoresonance masers (CARMs), gyroklystrons, gyro-TWT amplifiers, gyrotwystron amplifiers, gyro-BWO's, gyropeniotrons, magnicons, gyroharmonic converters, free electron masers (FEMs) and of vacuum windows for such high-power mm-wave sources. The highest CW powers produced by gyrotron oscillators, gyroklystrons and FEMs are, respectively, 340 kW (28 GHz), 10 kW (94 GHz) and 36 W (15 GHz). The IR (3.1 μ m) FEL at the Thomas Jefferson National Accelerator Facility obtained a record average power of 2.13 kW with an efficiency of 3.5% (with energy recovery).

STATUS DER ENTWICKLUNG VON HOCHLEISTUNGS-GYRO-RÖHREN UND FREI-ELEKTRONEN-MASERN STAND: ENDE 2002

Übersicht

Gyrotronoszillatoren (Gyromonotrons) werden vorwiegend als Hochleistungsmillimeterwellenquellen für die 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 1 MW Gyrotrons mit Austrittsfenstern aus künstlichem Diamant ist 5 s bei 110 GHz (CPI und JAERI-TOSHIBA), 12 s bei 140 GHz (FZK-CRPP-CEA-TED) und 9 s bei 170 GHz (JAERI-TOSHIBA), mit Wirkungsgraden wenig über 30%. Durch den Einsatz von Kollektoren mit einstufiger Gegenspannung (zur Energierückgewinnung) werden Gesamtwirkungsgrade von 45-50% erreicht. Der Energieweltrekord von 160 MJ (0,89 MW mit 180 s Pulslänge bei 140 GHz) bei Leistungen höher als 0,8 MW wird von der Europäischen FZK-CRPP-TED-CEA-Zusammenarbeitsgemeinschaft gehalten, wobei die Beschränkung der Pulslänge auf 180 s durch die Hochspannungsversorgung gegeben ist ($I_{\text{beam}} \approx 40$ A). Bei geringerem Strahlstrom ($I_{\text{beam}} = 26$ A) wurden sogar 506 MJ (0,54 MW bei 937 s) erreicht. Der längste Schuss dauerte 1300 s bei einer Ausgangsleistung von 0,26 MW. Diese Langpulse sind durch einen Druckanstieg in der Röhre begrenzt. Eine maximale Ausgangsleistung von 1,2 MW bei 4,1 s Pulslänge wurden mit dem JAERI-TOSHIBA 110 GHz Gyrotron erzeugt. Das russische 170 GHz ITER-Gyrotron erreichte 0,5 MW bei 80 s Pulslänge, das japanische 0,3 MW bei 60 s. Gyrotrons zur Plasmadiagnostik arbeiten bei Frequenzen bis zu 650 GHz bei $P_{\text{out}} = 40$ kW und $\tau = 40$ μ s ($\eta \geq 4\%$). Gyrotronoszillatoren finden jedoch auch in der Materialprozesstechnik erfolgreich Verwendung. Dabei werden Röhren mit folgenden Parametern eingesetzt: $f \geq 24$ GHz, $P_{\text{out}} = 10$ -50 kW, CW, $\eta \geq 30\%$. In diesem Beitrag wird auf den aktuellen experimentellen Stand bei der Entwicklung von Hochleistungs-Gyrotronoszillatoren für Langpuls- und Dauerstrichbetrieb sowie von gepulsten Gyrotrons zur Plasmadiagnostik eingegangen. Außerdem wird auch kurz über den neuesten Stand der Entwicklung von Gyrotrons mit koaxialem Resonator, Gyrotrons für technologische Anwendungen, relativistischen Gyrotrons, quasi-optischen Gyrotrons, Zyklotron-Autoresonanz-Masern (CARMs) mit schneller oder langsamer Welle, Gyroklystrons, Gyro-TWT-Verstärkern, Gyrotwystron-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 Gyrotronoszillatoren, Gyroklystrons und FEMs erzeugten CW-Leistungen sind 340 kW (28 GHz), 10 kW (94 GHz) bzw. 36 W (15 GHz). Der IR (3.1 μ m) FEL der Thomas Jefferson National Accelerator Facility erreichte eine Rekord-Durchschnitts-Leistung von 2.13 kW bei einem Wirkungsgrad von 3.5% (mit Energierückgewinnung).

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1 Introduction

The possible applications of gyrotron oscillators and other cyclotron-resonance maser (CRM) fast-wave devices span a wide range of technologies [1-4]. 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, nonlinear spectroscopy, materials processing and plasma chemistry.

Most work on CRM devices has investigated the conventional gyrotron oscillator (gyromonotron) [5-16] in which the wave vector of the radiation in an open-ended, irregular cylindrical waveguide cavity is transverse to the direction of the applied magnetic field, resulting in radiation near the electron cyclotron frequency or at one of its harmonics. Long pulse and CW gyrotron oscillators delivering output powers of 100-960 kW at frequencies between 28 and 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 [17-22] and stellarators [23-29]. 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 ($B \cong 6$ 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 [18,26,30-33]. 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 TEM₀₀ Gaussian beam mode. Single-mode 110-170 GHz gyromonotrons with conventional cylindrical cavity, capable of 1 MW per tube, CW, and 2 MW coaxial-cavity gyrotrons are currently under development. There has been continuous progress towards higher frequency and power but the main issues are still the long pulse or CW operation and the appropriate mm-wave vacuum window. The availability of sources with fast frequency tunability would permit the use of a simple, non-steerable mirror antenna at the plasma torus for local current drive experiments [34,35]. Frequency tuning has been shown to be possible on quasi-optical Fabry-Perot cavity gyrotrons [36,37] as well as on cylindrical cavity gyrotrons with step tuning (different operating cavity modes) [38-48].

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 [49,50] (Tables II-XII) but also refers to the development of very high frequency gyromonotrons for active plasma diagnostics [51-56] (Tables XIII-XVI) and 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 [1-4,57-60]. 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 employing permanent magnet systems [61-65]. The state-of-the-art in this area of industrial gyrotrons is summarized in Table XVII.

The next generation of high-energy physics accelerators and the next frontier in understanding of elementary particles is based on the supercollider. For normal-conducting linear electron-positron colliders that will reach center-of-mass energies of > 1 TeV it is thought that sources at 17 to 35 GHz with $P_{\text{out}} = 300$ MW, $\tau = 0.2$ μs and characteristics that will allow approximately 1000 pulses per second will be necessary as drivers [66-68]. 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 [69-74]. 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), gyrokystrons (Table XXIII and XXIV), gyrotron travelling wave tube amplifiers (Gyro-TWT) (Table XXV and XXVI), gyrotwistrons (Table XXVII), 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 status report updates and supplements the experimental achievements in the development of gyro-devices, free electron masers and of vacuum windows for such high-power mm-wave sources reviewed in [3,4,30-33] and in the KfK Report 5235 (Oct 1993) and the FZKA Reports 5564 (Apr 1995), 5728 (Mar 1996), 5877 (Feb 1997), 6060 (Feb 1998), 6224 (Jan 1999), 6418 (Feb 2000), 6588 (Mar 2001) and 6708 (Feb 2002) with the same title.

2 Classification of Fast-Wave Microwave Sources

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

The condition for coherent radiation is that the contribution from the electrons reinforces the original emitted radiation in the oscillator or the incident electromagnetic wave in the amplifier. This condition is satisfied if a bunching mechanism exists to create electron density variations of a size comparable to the wavelength of the imposed electromagnetic wave. To achieve such a mechanism, a resonance condition must be satisfied between the periodic motion of the electrons and the electromagnetic wave in the interaction region [14,75]

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

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:

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

where e and m_0 are the charge and rest mass of an electron, γ is the relativistic factor, and B_0 is the magnitude of the guide magnetic field. A group of relativistic electrons gyrating in a strong magnetic field will radiate coherently due to bunching caused by the relativistic mass dependence of their gyration frequency. Bunching is achieved because, as an electron loses energy, its relativistic mass decreases and it thus gyrates faster. The consequence is that a small amplitude wave's electric field, while extracting energy from the particles, causes them to become bunched in gyration phase and reinforces the existing wave electric field. The strength of the magnetic field determines the radiation frequency.

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

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

The operating frequency of such devices, an example of which is the FEM [76-80], 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 [5,81]: Richard Twiss in Australia [82], Jürgen Schneider in the US [83] and Andrei Gaponov in Russia [84]. 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 [85]. 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 [5,81]. 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 [86] (where the term "electron cyclotron maser" was apparently coined) and in Russia [87].

Many configurations can be used to produce coherent radiation based on the electron cyclotron maser instability. The departure point for designs based on a particular concept is the wave-particle interaction. Dispersion diagrams, also called ω - k_z plots or Brillouin diagrams [1,88-91], 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 $k_{\perp} = X_{mn} / R_0$ where X_{mn} is the n th root of the corresponding Bessel function (TM_{mn} modes) or derivative (TE_{mn} modes) and R_0 is the waveguide radius. Phase velocity synchronism of the two waves is given in the intersection region. The interaction can result in a device that is either an oscillator or an amplifier. In the following subsections, the different ECM devices are classified according to their dispersion diagrams.

3.1 Gyrotron Oscillator and Gyroklystron Amplifier

Gyrotron oscillators were the first ECMs to undergo major development. Increases in device power were the result of Russian developments from the early 1970s in magnetron injection guns, which produce electron beams with the necessary transverse energy (while minimizing the spread in transverse energies) and in tapered, open-ended waveguide cavities that maximize efficiency by tailoring the electric field distribution in the resonator [5-13].

Gyrotron oscillators and gyroklystrons are devices which usually utilize only weakly relativistic electron beams ($E_{\text{beam}} < 100$ keV, $\gamma < 1.2$) with high transverse momentum (pitch angle $\alpha = v_{\perp}/v_z > 1$) [90]. 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 ($v_{\text{ph}} = \omega/k_z \gg c$) 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 [88-91]. 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_0 , a mode represented by X_{mn} and oscillating at frequency ω is only excited over a narrow range of B_0 . By variation of the magnetic field, a sequence of discrete modes can be excited. The frequency scaling is determined by the value of B_0/γ . Modern high-power high-order volume mode gyrotron oscillators for fusion plasma applications employ an internal quasi-optical mode converter with lateral microwave output [90] and a single-stage depressed collector (SDC) for energy recovery (Tables II-VIII) (Fig.5). 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 [5-13,62-65,88-91]. At low voltages, the number of electron orbits

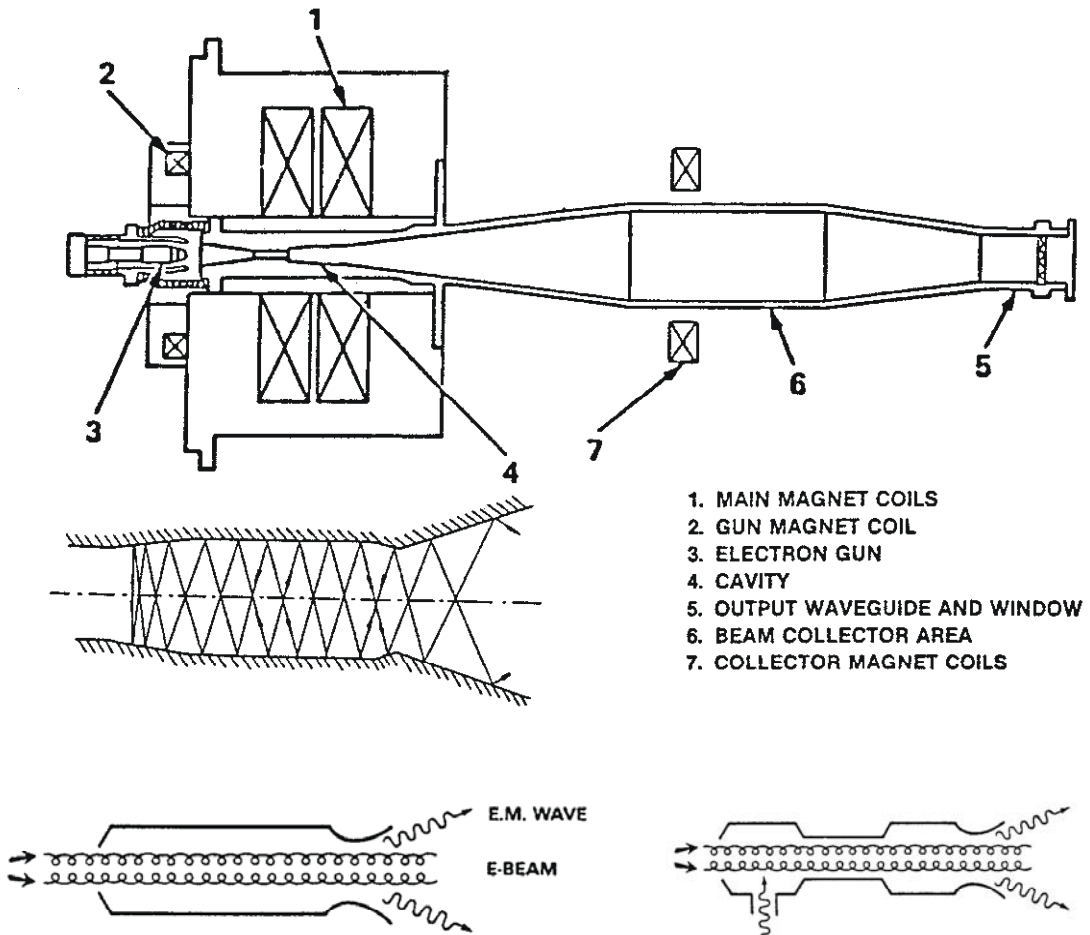


Fig. 1: Schematic of VARIAN CW gyrotron oscillator [10,15] and scheme of irregular waveguide cavities of gyromonotron oscillator (left) and gyrokylystron amplifier [88].

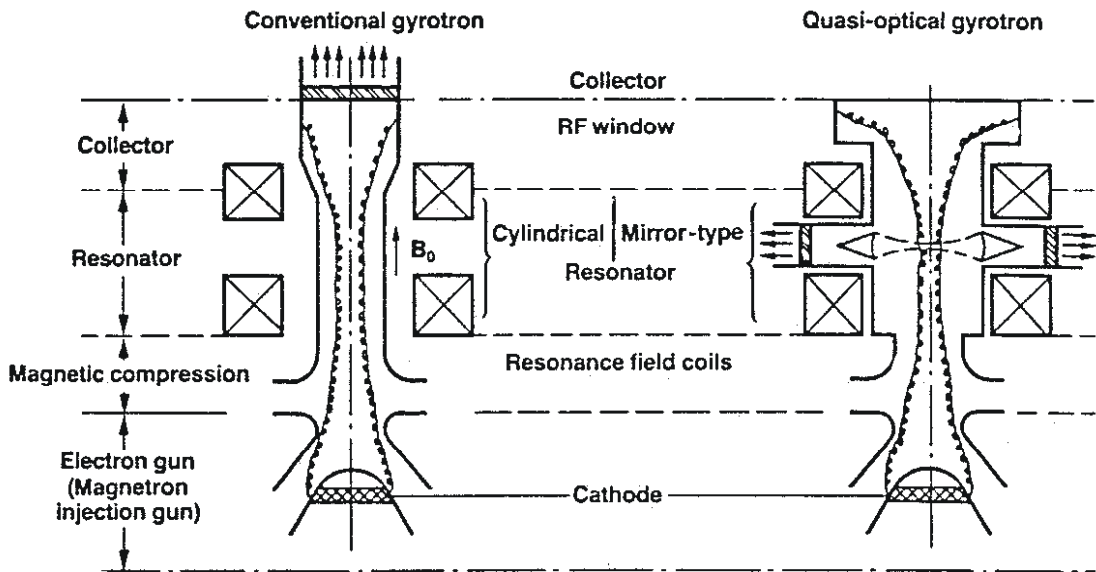


Fig. 2: Principle of a conventional gyrotron with cylindrical resonator and of a quasi-optical gyrotron with mirror resonator [36,37].

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.

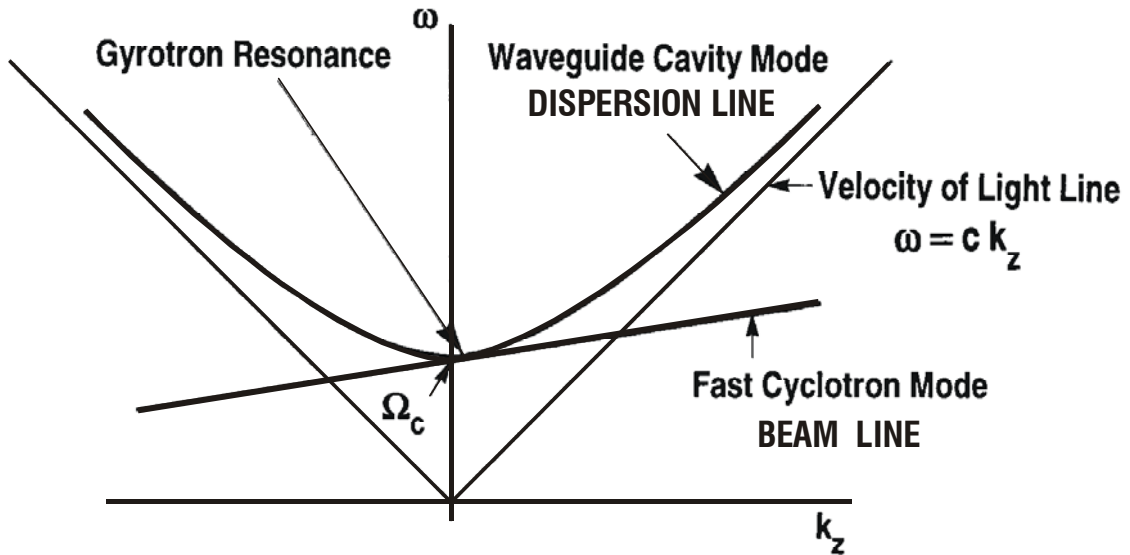


Fig. 3: Dispersion diagram of gyrotron oscillator (fundamental resonance).

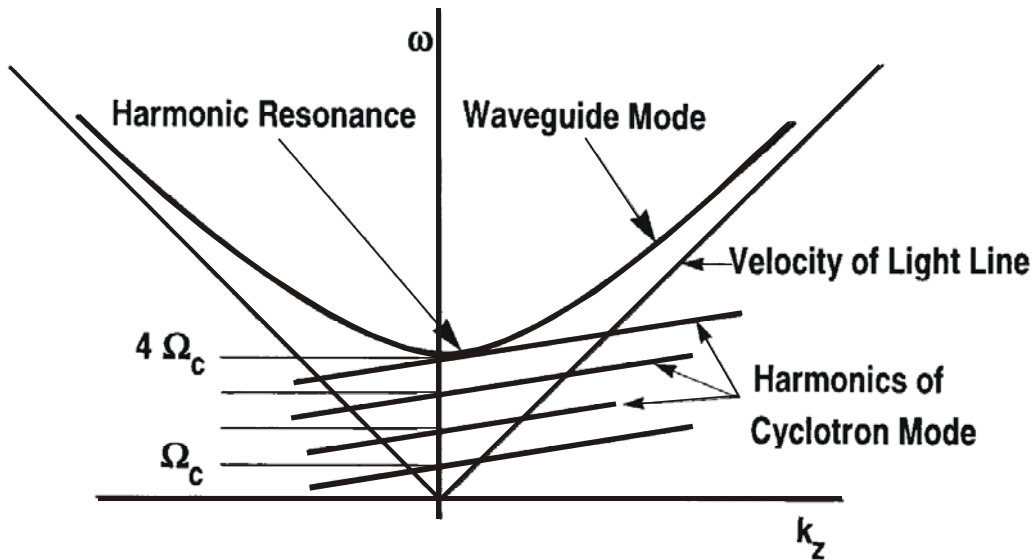


Fig. 4: Dispersion diagram of harmonic frequency gyrotron oscillator.

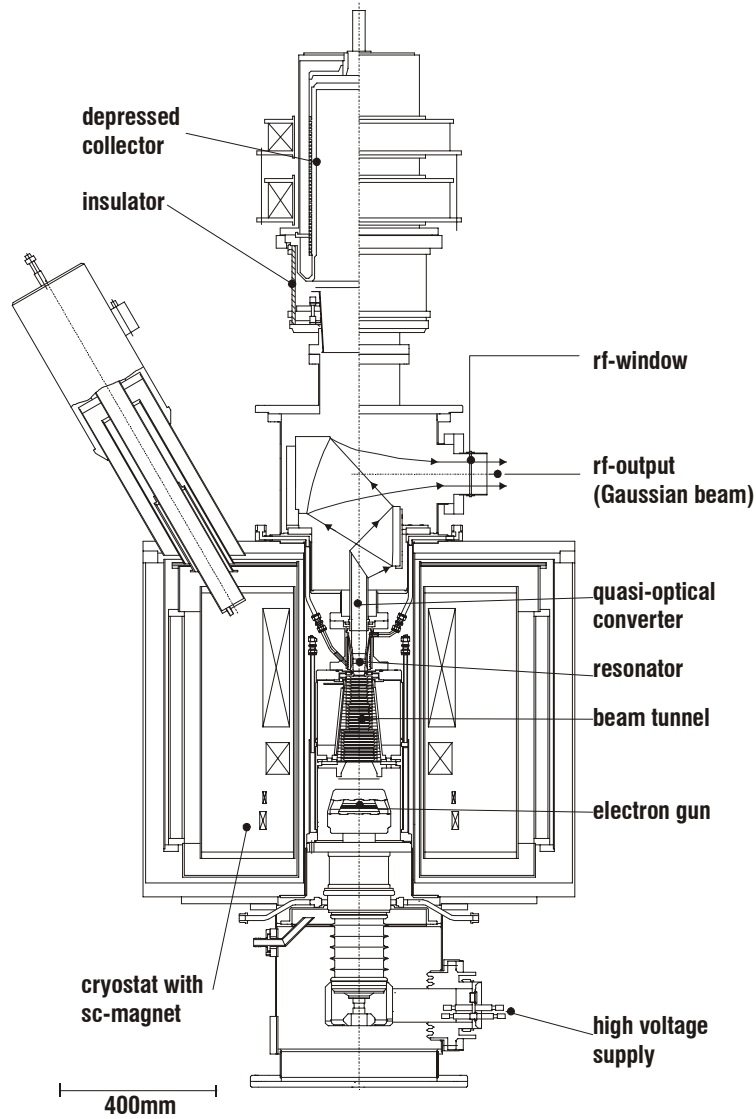


Fig. 5: Schematic layout of modern high-order volume mode gyrotron with quasi-optical mode converter and single-stage depressed collector.

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 $v_{\text{ph}} \cong c$, the increase in cyclotron frequency due to extraction of beam energy (decrease of γ) nearly compensates the decrease in the Doppler shifted term. Therefore, if the resonance condition is initially fulfilled, it will continue to be satisfied during the interaction. This phenomenon is called autoresonance, and the cyclotron maser devices operating in the relativistic Doppler-shifted regime are called cyclotron autoresonance masers [14,75]. Fig. 6 shows how

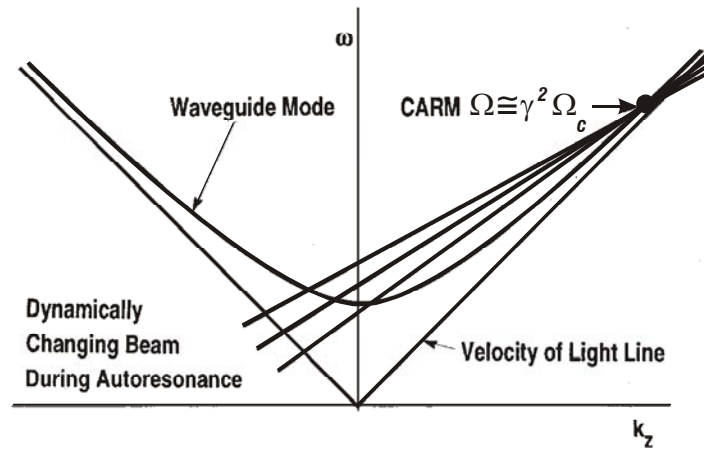


Fig. 6: Dispersion diagram of the cyclotron autoresonance maser (CARM).

the Brillouin diagram of the fast cyclotron wave changes during the autoresonance interaction such that the working frequency ω remains constant even though both Ω_c and v_z are changing. The CARM interaction corresponds to the upper intersection and is based on the same instability mechanism as that of the gyrotron but operated far above cutoff. The instability is convective, so feedback, e.g. by a Bragg resonator (see Fig. 7) [75] 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.

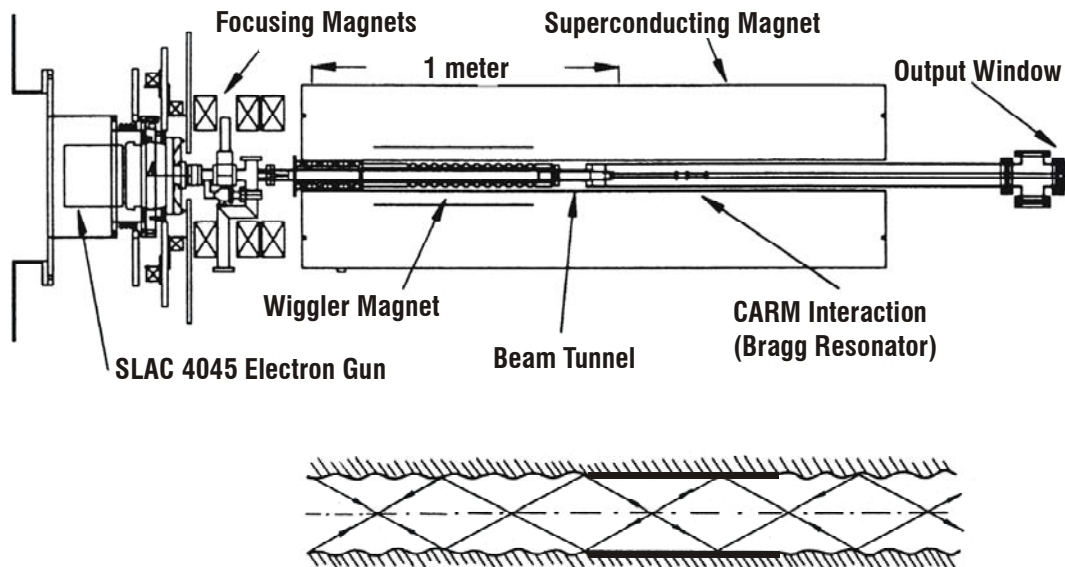


Fig. 7: Schematic of the long-pulse MIT CARM oscillator experiment [92] and scheme of a Bragg resonator [75].

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% [75,92].

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 [93-96], 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

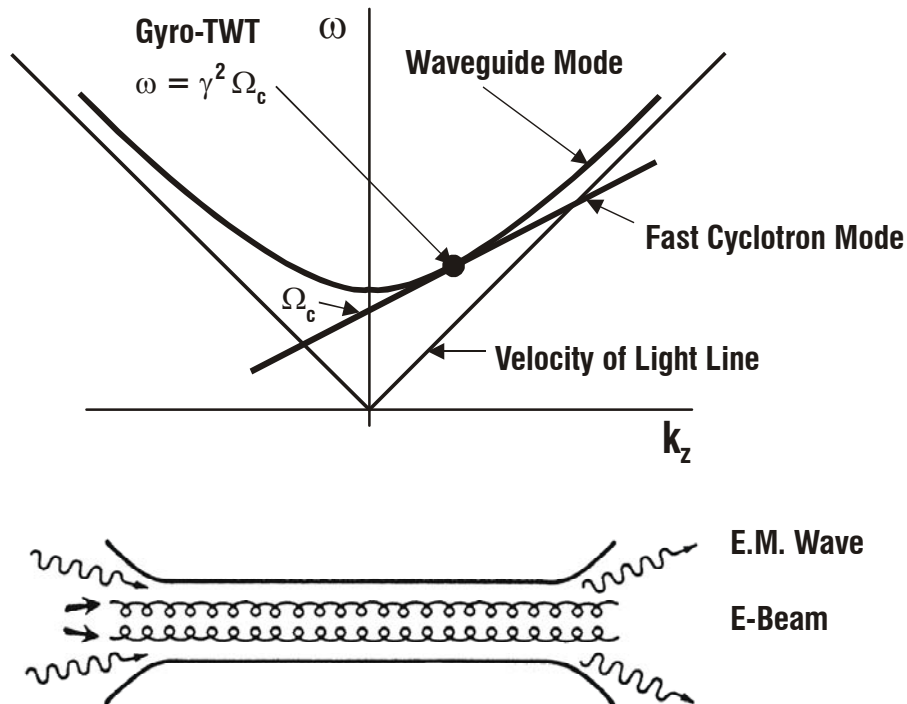


Fig. 8: Dispersion diagram and scheme of interaction circuit of Gyro-TWT amplifier.

velocity of the waveguide mode is nearly equal to v_z . In the gyro-TWT regime ($\omega/k_z \gg c$), 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. Recent devices employ tapered magnetic field and interaction circuit as well as two stages in order to optimize the beam-wave interaction along the waveguide [97,98].

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 [99].

The gyrotwystron [5], 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 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 [100]. 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

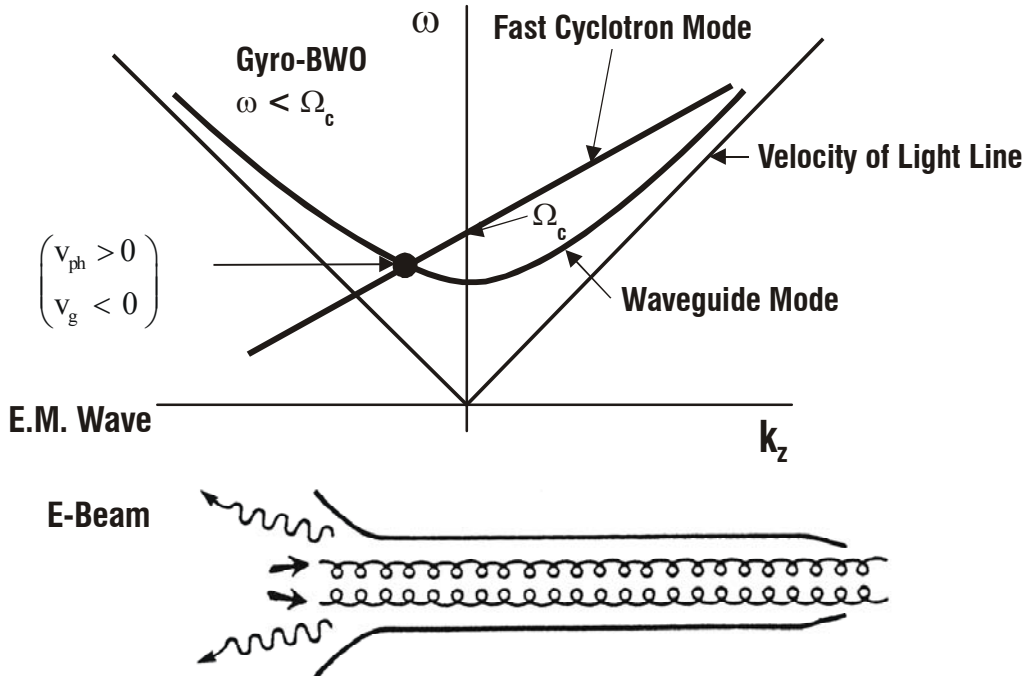


Fig. 9: Dispersion diagram and scheme of interaction circuit of Gyro-BWO.

operation is now governed by the slope of the line, which is a function of v_z , and thus of the beam acceleration voltage U_{beam} . Consequently, just as in the case of other BWOs (e.g. carcinotron), the frequency of oscillations can be continuously changed very fast over a broad range, using U_{beam} in place of B_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, BWO and twystron [5]. In both cases the primary energy modulation of electrons gives rise to bunching (azimuthal or longitudinal) which is inertial. The bunching continues even after the primary modulation field is switched off (at the drift section of a klystron-type devices). This analogy suggests the correspondence between linear-beam (O-type) devices and various types of gyro-devices. Table I presents the schematic drawings of devices of both classes and the orbital efficiencies calculated using a simplified uniform approximation for the longitudinal structure of the RF field in the gyromonotron ($s=1$) [5]. 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.

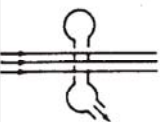
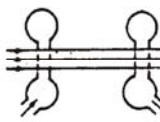
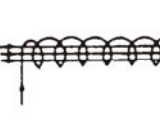
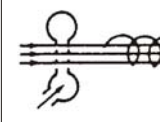
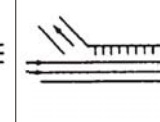
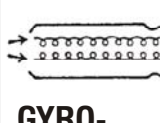
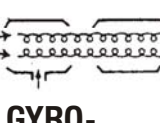
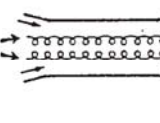
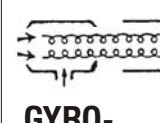
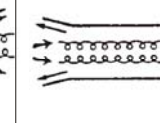
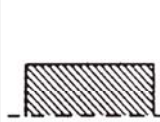

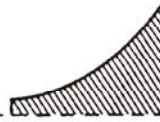

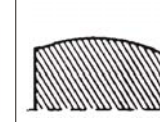
"O" TYP DEVICES					
	MONOTRON	KLYSTRON	TWT	TWYSTRON	BWO
TYPE OF GYRO-DEVICE					
	GYRO-MONOTRON	GYRO-KLYSTRON	GYRO-TWT	GYRO-TWYSTRON	GYRO BWO
MODEL RF-FIELD STRUCTURE					
MODEL ORBITAL EFFICIENCY	0.42	0.34	0.7	0.6	0.2

Table I: Overview of gyro-devices and comparison with corresponding conventional linear-beam (O-type) devices [5].

In Tables 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 employs an axis-encircling electron beam in which the trajectory of each electron takes it around the axis of the cylindrical interaction region. Peniotron and gyropeniotron are driven by an interaction that is phased quite differently from the ECM interaction; in practice, the peniotron and ECM mechanisms compete [88-91,101].

4 Magnicons and Gyroharmonic Converters

The magnicon is a member of the class of scanning-beam amplifier tubes [12,102]. 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 indifferently, very high efficiencies can be achieved.

Recently, higher perveance versions of the magnicon have been developed [102], 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 [103]. 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 [103-105].

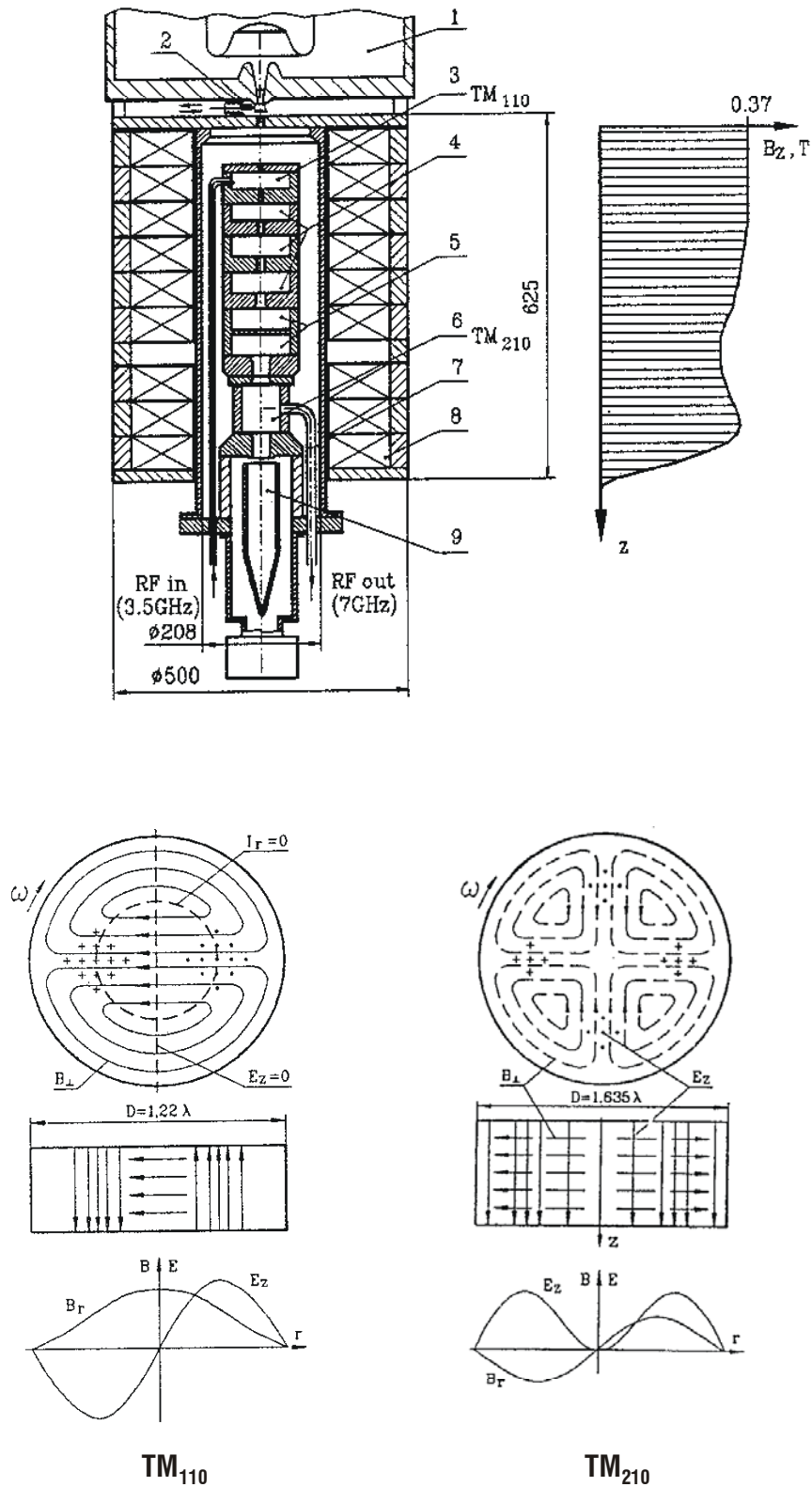


Fig. 10: Schematic layout of the magnicon: 1 - electron source; 2 - vacuum valve; 3 - drive cavity; 4 - gain cavity; 5 - penultimate cavity; 6 - output cavity; 7 - waveguide (x2); 8 - solenoid; 9 - collector [102].

5 Principle of Free Electron Lasers

Free electron lasers (FELs) differ from the other high-power microwave sources considered in this report in that they have demonstrated output over a range of frequencies extending far beyond the microwave spectrum, well into the visible and ultraviolet range [76-80,88,89]. To achieve this spectral versatility, FELs exploit relativistic beam technology to upshift the electron "wiggle" frequency by an amount roughly proportional to γ^2 (see Fig. 11 and Section 2). In this respect, perhaps a more descriptive name is that coined by R.M. Phillips [106]: 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 [5,14,75]. 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) [107].

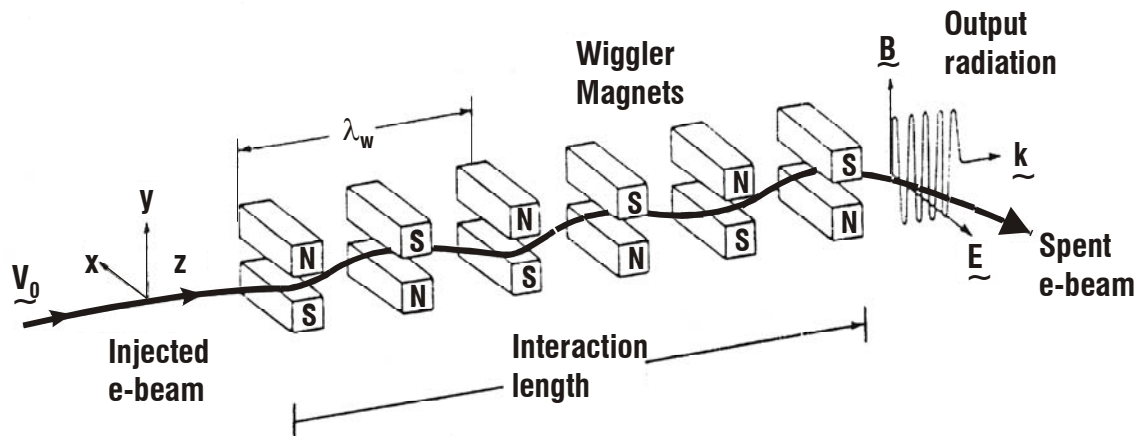


Fig. 11: The basis FEM configuration. Electrons in an injected electron beam undulate in the periodic magnetic field of the wiggler.

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 [4,108-118]. 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 [108-117] was terminated in the autumn of 2001. The highest CW power generated by a FEM is 36 W (15 GHz) [119] whereas the IR ($3.1 \mu\text{m}$)-FEL at the Thomas Jefferson National Accelerator Facility obtained a record average power of 2.13 kW at 3.5% efficiency employing beam energy recovery [111].

6 Gyrotron Oscillators and Microwave Vacuum Windows for Plasma Heating

Institution	Frequency [GHz]	Mode		Power [MW]	Efficiency [%]	Pulse length [s]
		cavity	output			
ABB, Baden [90,123]	8	TE ₀₁	TE ₀₁	0.35	35	0.5
	39	TE ₀₂	TE ₀₂	0.25	42	0.1
CPI ²⁾ , Palo Alto [10,15,124-128]	8	TE ₂₁	TE ₁₀	0.5 (dual output)	33	1.0
	28	TE ₀₂	TE ₀₂	0.34 (0.2)	37 (45)	CW
	35	TE ₀₂	TE ₀₂	0.2	35	CW
	53.2,56,60	TE _{01/02}	TE ₀₂	0.23	37	CW
		TE _{01/02}	TE ₀₂	0.21	36	3
	70.15	TE _{10,3}	TEM ₀₀	0.6	47 (SDC)	2.25
	84	TE _{15,2}	TE _{15,2/4}	0.5	28	0.1
				0.89	28	0.001
CPI ²⁾ , NIFS Palo Alto, Toki [28,29,123-133]	84	TE _{15,4}	TEM ₀₀	0.56	44 (SDC)	2.0
	84	TE _{15,3}	TEM ₀₀	0.5	29	2.0
				0.4	28	10.5
				0.2	21	30
				0.1	14	CW
				0.59	41 (SDC)	0.001
				0.25	32 (SDC)	0.2
				0.5	40	0.5
GYCOM-N (SALUT, IAP) Nizhny Novgorod [11,39,40,133-136]	28	TE ₄₂	TEM ₀₀	0.5	40	0.5
	37.5	TE ₆₂	TEM ₀₀	0.5	35	0.1
	53.2	TE ₈₃	TEM ₀₀	0.5	40	0.1
				0.3	36	1.0
	70	TE ₉₃	TEM ₀₀	0.68	48 (SDC)	3.0
	75	TE ₉₄	TEM ₀₀	0.5	37	0.1
	82.5	TE _{11,3}	TE _{11,3}	1.0	50	0.0001
				1.5	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
				0.05	50 (SDC)	CW
84	TE _{12,5}	TEM ₀₀	0.88	54 (SDC)	3.0	
HUGHES, Torrance [88]	60	TE ₀₂	TE ₀₂	0.2	35	0.1
IAP, Nizhny Novgorod [137]	25(2Ω _c)	TE ₀₃	TE ₀₃	0.8	40 (twin e-beam)	0.0001
IECAS, Beijing [138,139]	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
0.0058				16	0.000015	
LAP/INPE, Sao Paulo [140]	24.2	TE ₁₂	TE ₁₂	0.0063	18.5	0.000015
	30.4	TE ₂₂	TE ₂₂	0.35	29	0.1
MITSUBISHI, Amagasaki KYOTO UNIV. [141]	88	TE _{8,2}	TEM ₀₀	0.35	29	0.1
NEC, Kawasaki [142]	35	TE ₀₁	TE ₀₁	0.1	30	0.001
NRL, Washington D.C. [88,143]	35	TE ₀₁	TE ₀₁	0.15	31	0.02
	35	TE ₀₄	TE ₀₄	0.475	38	0.001
	35	TE ₂₄	TE ₂₄	0.43	40	0.001
PHILIPS ¹⁾ , Hamburg [144]	70	TE ₀₂	TE ₀₂	0.14	30	CW
SPbSTU, St. Petersburg FZK Karlsruhe [146]	74.7	TE _{12,3}	TE _{12,3}	0.07	20	0.000001
THALES ED ³⁾ , Velizy [90,145]	8	TE ₅₁	TE ₅₁	1.0	45	1.0
	35	TE ₀₂	TE ₀₂	0.2	43	0.15
TOSHIBA, Otawara [147]	28	TE ₀₂	TE ₀₂	0.2	35.7	0.075
	41	TE ₀₂	TE ₀₂	0.2	31.3	0.1
	56	TE ₀₂	TE ₀₂	0.2	32.9	0.1
	70	TE ₀₂	TE ₀₂	0.025	28.4	0.001
UESTC, Chengdu [148]	35(3Ω _c)	TE ₅₁ /TE ₅₂	TE ₅₂	0.15	10	0.000001

PM, 100 kg

SDC: Single-stage Depressed Collector

¹⁾ formerly VALVO, ²⁾ Communications & Power Industries, formerly VARIAN, ³⁾ formerly Thomson TE

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

Institution	Frequency [GHz]	Mode cavity	Mode output	Power [MW]	Efficiency [%]	Pulse length [s]
CPI²⁾, Palo Alto [10,15,126-128,149-154]	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	1.05	31	5.0
				0.6	31	10.0
			0.106	21	CW	
FZK¹⁾, Karlsruhe [41-47,155-165]	117.9	TE _{19,5}	TEM ₀₀	1.55	31	0.007
				1.55	49.5 (SDC)	0.007
	132.6	TE _{9,4}	TE _{9,4}	0.42	21	0.005
GYCOM-M (TORIY, IAP) Moscow, N. Novgorod [11,87,136,166-173]	110	TE _{19,5}	TEM ₀₀	1.2	40	0.0001
				1.0	65(SDC)	0.0001
				0.93	36	2.0
				0.5	35	5.0
				0.35	33	10.0
GYCOM-N (SALUT, IAP) N. Novgorod [11,39,40,133-136,173-176]	104	TE _{18,7}	TEM ₀₀	0.98	46.5 (SDC)	0.5
	106.4	TE _{15,4}	TEM ₀₀	0.5	33	0.2
	110	TE _{15,4}	TEM ₀₀	0.5	33	1.0
	111.5	TE _{19,6}	TEM ₀₀	1.0	32	0.0001
	129	TE _{17,7}	TEM ₀₀	0.5	33	0.5
JAERI, TOSHIBA Naka, Otawara [177-187]	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	1.2	38 (SDC)	4.1
				1.0	36 (SDC)	5.0
	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 [188,189]	120	TE _{02/03}	TE ₀₃	0.16	25	0.06
	120	TE _{15,2}	TE _{15,2}	1.02	32.5	0.0002
				0.46	30	0.1
				0.25	30	0.21
THALES ED³⁾, Velizy [90,145]	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 ED³⁾, CEA,CRPP, FZK [190-195]	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⁾ formerly KfK, ²⁾ Communications & Power Industries, formerly VARIAN, ³⁾ 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]
CPI³, Palo Alto [10,15,125-128]	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
				0.2 (0.4)	31	avg. (peak)
140.2	TE _{28,7}	TEM ₀₀	0.90	38 (SDC)	0.005	
FZK¹, PHILIPS² [90,155]	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
	FZK, Karlsruhe [41-47,90,155-165,196-210]	140.2	TE _{10,4}			TEM ₀₀
0.50				48 (SDC)	0.03	
0.46				51 (SDC)	0.2	
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
				1.0	50 (SDC)	12
FZK¹, CRPP, THALES ED⁴, CEA [16,193,211,214]		139.8	TE _{28,8}	TEM ₀₀	0.92	42 (SDC)
	0.89				41 (SDC)	180
	0.54 (0.26)					937 (1300)
	0.96				36	1.2
GYCOM-M (TORIY, IAP) Moscow, N. Novgorod [11,48,134,136,168-173, 215-227]	140	TE _{22,6}	TEM ₀₀	0.54	36	3.0
				0.26	36	10
				0.1	35	80
				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
	139.82	TE _{22,8}	TEM ₀₀	0.84	37	3.5
				0.53	32	6.0
	170	TE _{28,7}	TEM ₀₀	1.0	32.5	0.0001
	170	TE _{25,10}	TEM ₀₀	1.4	35	0.0001
				1.0	62 (SDC)	0.0001
	170	TE _{25,10}	TEM ₀₀	1.0	45 (SDC)	1.5
				0.85	48 (SDC)	5.0
				0.5	36 (SDC)	80
0.8				32	0.8	
GYCOM-N (SALUT, IAP) N. Novgorod [11,39,40,133-136,173,176, 215]	140	TE _{22,6}	TEM ₀₀	0.88	50.5(SDC)	1.0
				0.55	33	2.0
				0.99	47 (SDC)	0.5
				0.5	30	0.7
JAERI, TOSHIBA Naka, Otawara [182-187,228-235]	170	TE _{22,6}	TEM ₀₀	0.45	19	0.05
				0.25	19	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
				0.9	43.4 (SDC)	9.2
				0.5	46 (SDC)	30
				0.3	40 (SDC)	60
NIFS, TOSHIBA Toki, Otawara [27-29,131-132,236]	168	TE _{31,8}	TEM ₀₀	0.52	19	1.0
				0.52	30 (SDC)	1.0

SDC: Single-stage Depressed Collector

¹⁾ formerly KfK, ²⁾ formerly VALVO, ³⁾ Communications & Power Industries, formerly VARIAN,

⁴⁾ formerly Thomson TE

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	
FZK¹⁾ Karlsruhe [206-210,237-255] 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	
	167.14	TE _{32,17}	TEM ₀₀	1.22	25.6	yes	no	
IAP, Nizhny Novgorod [9,11,134,136,256-262] 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	
	103	TE _{22,13}	TE _{22,13}	1.6	38	no	no	
				1.0	40	yes	yes	
				0.7	30	yes	no	
				0.3	14	no	no	
	110	TE _{17,7}	TE _{17,7}	0.7	25	no	no	
	110	TE _{20,13}	TE _{20,13}	1.15	35	yes	no	
	110	TE _{21,13}	TE _{21,13}	1.0	35	yes	no	
	140	TE _{28,16}	TE _{28,16}	1.5	33.5	yes	no*	
			1.15	50 (SDC)	yes	no		
		TE _{76,2}	1.17	35.2	yes	yes		
		TEM ₀₀	1.1	30	yes	no		
			(dual-beam output)					
224 (2 Ω_c)	TE _{33,8}	TE _{33,8}	0.1	11	yes	no		
IAP, FZK¹⁾ Karlsruhe [237] Pulse length 30 μs	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 [263-265] Pulse length 3 μs	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, * very similar cavity and tube design

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

Institution	Frequency [GHz]	Mode cavity	Mode output	Power [MW]	Efficiency [%]	Pulse length [s]			
CPI ¹⁾ , Palo Alto [125-128]	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			
	140.2	TE _{27,8}	TEM ₀₀	0.9	38(SDC)	0.005			
CPI ¹⁾ , NIFS Palo Alto, Toki [27-29,131]	84	TE _{15,3}	TEM ₀₀	0.52	38(SDC)	0.5			
				0.5	29	2.0			
				0.59	41 (SDC)	0.001			
				0.25	32 (SDC)	0.2			
FZK ²⁾ , Karlsruhe [41-46,155-165,198-210]	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			
FZK ¹⁾ , CRPP, THALES ED ³⁾ , CEA [16,193,211-214]	162.3	TE _{25,7}	TEM ₀₀	2.1	53 (SDC)	0.001			
				1.48	50 (SDC)	0.007			
				139.8	TE _{28,8}	TEM ₀₀	1.0	50 (SDC)	12
				0.92	42 (SDC)	56			
				0.89	41 (SDC)	180			
				0.54 (0.26)		937 (1300)			
GYCOM-N (SALUT, IAP) Nizhny Novgorod [135,136,169,170,175,176]	70	TE _{9,3}	TEM ₀₀	0.68	48 (SDC)	3.0			
	82.7	TE _{10,4}	TEM ₀₀	0.65	38	3.0			
				0.65	53 (SDC)	0.03			
				0.05	50 (SDC)	CW			
				0.88	54 (SDC)	3.0			
	104	TE _{18,7}	TEM ₀₀	0.98	46.5 (SDC)	0.5			
	110	TE _{19,5}	TEM ₀₀	1.2	40	0.0001			
				1.0	65 (SDC)	0.0001			
	140	TE _{22,6}	TEM ₀₀	0.8	32	0.8			
				0.88	50.5 (SDC)	1.0			
140	TE _{22,10}	TEM ₀₀	0.99	47 (SDC)	0.5				
GYCOM-M (TORIY, IAP) Moscow, Nizhny Novgorod [48,136,225-227]	140	TE _{22,8}	TEM ₀₀	1.7	42	0.0001			
				1.2	68 (SDC)	0.0001			
				1.4	35	0.0001			
				1.0	62 (SDC)	0.0001			
				1.0	45 (SDC)	1.5			
				0.85	48 (SDC)	5.0			
NRL, Washington D.C. [266]	115	QOG	TEM ₀₀	0.5	36 (SDC)	80			
				0.60	9	10 ⁻⁵			
				0.43	12.7 (SDC)	10 ⁻⁵			
				0.20	16.1 (SDC)	10 ⁻⁵			
JAERI, TOSHIBA Naka, Otawara [177-187,228-235]	110	TE _{22,2}	TEM ₀₀	0.61	50 (SDC)	0.05			
				0.35	48 (SDC)	5.0			
	110	TE _{22,6}	TEM ₀₀	1.2	38 (SDC)	4.1			
				1.0	36 (SDC)	5.0			
	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
				0.9	43.4 (SDC)	9.2			
			0.5	46 (SDC)	30				
			0.3	40 (SDC)	60				
NIFS, TOSHIBA Toki, Otawara [27-29,132,236]	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⁾ Communications & Power Industries; formerly VARIAN, ²⁾ formerly KfK, ³⁾ formerly Thomson TE

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

Institution	Frequency [GHz]	Mode cavity	Mode output	Power [MW]	Efficiency [%]	Pulse length [s]		
FZK¹⁾, Karlsruhe [41-47,162-165,207-210]	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	TE _{20,5}	TEM ₀₀	1.0	27	0.001		
	125.3	TE _{21,5}	TEM ₀₀	1.0	27	0.001		
	128.9	TE _{22,5}	TEM ₀₀	0.9	24.5	0.001		
	132.6	TE _{20,6}	TEM ₀₀	0.85	23	0.001		
	136.2	TE _{21,6}	TEM ₀₀	0.9	24.5	0.001		
	140.1	TE _{22,6}	TEM ₀₀	1.0	27	0.001		
				1.6	60 (SDC)	0.007	optimized	
	143.7	TE _{23,6}	TEM ₀₀	1.1	30	0.001		
	147.4	TE _{24,6}	TEM ₀₀	1.1	30	0.001		
	151.2	TE _{25,6}	TEM ₀₀	1.05	28.5	0.001		
	154.9	TE _{23,7}	TEM ₀₀	0.95	26	0.001		
	158.5	TE _{24,7}	TEM ₀₀	1.1	30	0.001		
	162.3	TE _{25,7}	TEM ₀₀	1.0	27	0.001		
				1.48	50 (SDC)	0.007	optimized	
	166.0	TE _{26,7}	TEM ₀₀	1.0	26	0.001		
	GYCOM-N (SALUT, IAP) Nizhny Novgorod [39,40,48,136,176]	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		
111.7		TE _{19,6}	TEM ₀₀	1.37	42.9	0.0001		
124.3		TE _{20,7}	TEM ₀₀	1.18	37.0	0.0001		
127.6		TE _{21,7}	TEM ₀₀	1.33	41.6	0.0001		
140.1		TE _{22,8}	TEM ₀₀	1.42	43.3	0.0001		
				1.2	68 (SDC)	0.0001		
152.6		TE _{23,9}	TEM ₀₀	1.44	44.2	0.0001		
156.0		TE _{24,9}	TEM ₀₀	1.01	36.1	0.0001		
140.0		TE _{22,8}	TEM ₀₀	1.7	42	0.0001		
				1.2	68 (SDC)	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			

SDC: Single-stage Depressed Collector;

¹⁾ formerly KfK

Table VII: Step-tunable conventional cavity 1 MW gyrotron with broadband Quartz Brewster angle window at FZK ($U_c = 82$ kV, $I_b = 45$ A). Pulse duration up to 0.007 s with Silicon Nitride (Kyocera SN-287) Brewster angle window. Two and three-frequency and multi-frequency GYCOM-N gyrotrons with matched plane BN windows.

The FZK 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 [47]. 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.

Institution	Frequency [GHz]	Mode cavity	Mode output	Power [MW]	Efficiency [%]	Pulse length [s]
FZK ¹⁾ , Karlsruhe [46,248-251,253,254]	136.3	TE _{26,14}	TEM ₀₀	1.02	23.5	0.001
	138.7	TE _{27,14}	TEM ₀₀	1.14	26.1	0.001
	140.8	TE _{28,14}	TEM ₀₀	0.92	24.0	0.001
	142.2	TE _{26,15}	TEM ₀₀	0.90	20.6	0.001
	144.4	TE _{27,15}	TEM ₀₀	0.96	23.1	0.001
	146.7	TE _{28,15}	TEM ₀₀	1.13	25.6	0.001
	149.0	TE _{29,15}	TEM ₀₀	1.08	22.9	0.001
	151.1	TE _{30,15}	TEM ₀₀	1.00	21.3	0.001
	152.4	TE _{28,16}	TEM ₀₀	0.75	20.8	0.001
	154.6	TE _{29,16}	TEM ₀₀	0.94	23.4	0.001
	156.9	TE _{30,16}	TEM ₀₀	1.24	25.4	0.001
	159.2	TE _{31,16}	TEM ₀₀	1.04	23.9	0.001
	160.7	TE _{29,17}	TEM ₀₀	0.99	20.7	0.001
	162.8	TE _{30,17}	TEM ₀₀	0.98	20.7	0.001
	165.1	TE _{31,17}	TEM ₀₀	1.24	26.3	0.001
				1.24	41 (SDC)	0.001
	167.2	TE _{32,17}	TEM ₀₀	1.22	25.6	0.001

SDC: Single-stage Depressed Collector;

¹⁾ formerly KfK

Table VIII: Step-tunable 1 MW gyrotron with coaxial cavity (tapered and longitudinally corrugated inner rod) and broadband Silicon Nitride (Kyocera SN-287) Brewster window ($U_c = 90$ kV, $I_b = 52$ A).

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 [261,262]. By biasing the inner rod of the FZK 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.

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	FZK/IAP/IPF/IPP
		370	140	1.3	FZK/IAP/IPF/IPP
sapphire	single-disk LHe edge cooled	410	110	1.0	JAERI/TOSHIBA
		500	110	0.5	JAERI/GA
sapphire	double-disk FC75 face cooled	200	60	CW	CPI
		400	84	10.5	NIFS/CPI
		350	110	5.0	JAERI/TOSHIBA
		200	140	CW	CPI
sapphire	distributed water cooled	65**	110	0.3	GA/JAERI
		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
		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
		1200	110	4.1	JAERI/TOSHIBA
		340	118	50	FZK/CEA/TED
		300	118	111	FZK/CEA/TED
		1000	140	12	FZK/CEA/CRPP/TED
		920	140	56	FZK/CEA/CRPP/TED
		890	140	180	FZK/CEA/CRPP/TED
		540	140	937	FZK/CEA/CRPP/TED
		260	140	1300	FZK/CEA/CRPP/TED
		520	140	0.5	CPI
		1000	170	1.5	GYCOM-M/FZK
		500	170	80	GYCOM-M/FZK
		900	170	9.2	JAERI/TOSHIBA
		450	170	47	JAERI/TOSHIBA
300	170	60	JAERI/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 [11,15,16,30,90,126-128,132,136,154,165-187,190-195,211-214,222-227, 232-236,267-301].

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.
Thermal Conductivity k [W/mK]	260	55	59	40	150	2000
Ultimate Bending Strength σ_B [MPa]	140	80	800	410	1000	500
Poissons Number ν	0.3	0.25	0.28	0.22	0.1	0.1
Density ρ [g/cm ³]	2.85	2.3	3.4	4.0	2.3	3.52
Specific Heat Capacity c_p [J/g K]	1.05	0.8	0.6	0.8	0.7	0.52
Young's Modulus E [GPa]	345	70	320	385	190	1050
Therm. Expans. Coeff. α [10 ⁻⁶ /K]	7.2	3	2.4	5.5	2.5	1.0
Permittivity (145 GHz) ϵ_r'	6.7	4.7	7.84	9.4	11.7	5.67
Loss Tangent (145 GHz) $\tan\delta$ [10 ⁻⁵]	70	115	30	20	0.35	2
Metallizing/Brazing Bakeout	o.k.	o.k.	o.k. 550°C	o.k. 550°C	o.k. 550°C	o.k. 450°C
Possible Size \varnothing [mm]	150	145	300	270	127	120
Cost	medium	medium	high	high	low	very high
Failure Resistance R' $R' = k\sigma_B(1-\nu)/E\alpha$	10.3	15.7	44.5	6.0	284	858
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
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) [288].

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 $n(0.3 \cdot 10^{21} \text{ n/m}^2)$ 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) [288].

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 [30-34,288]. The features of beryllia, boron nitride, silicon nitride (Kyocera SN-287), sapphire, Au-doped silicon and CVD diamond at room temperature and of sapphire, Au-doped silicon and CVD diamond at cryo-temperatures are summarized in Tables X and XI, where

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

and

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

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 JAERI 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) [190-195] 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 cooling 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 [276].

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 [30-34,288]. 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 [30-34,288].

7 Very High Frequency Gyrotron Oscillators

Institution	Frequency [GHz]	Mode	Power [kW]	Efficiency [%]	Pulse length [ms]
CPI¹⁾, Palo Alto [302]	250	TE _{11,1} /TE _{11,2}	10	3.4	0.1
IAP, N. Novgorod [51,52,303]	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 [304,305]	209	TE ₉₂	15	3.5	0.001
	241	TE _{11,2}	25	6.5	0.001
	302	TE ₃₄	4	1.5	0.0015
	339	TE _{10,2}	4	3	0.0015
	363	TE _{11,2}	7	2.5	0.0015
	417	TE _{10,3}	15	6	0.0015
	457	TE _{15,2}	7	2	0.0015
	467	TE _{12,3}	22	3.5	0.0015
	503	TE _{17,2}	10	5.5	0.0015
UNIVERSITY, Fukui [53-56,306-313]	383	TE ₂₆	3	3.7	1
	402	TE ₅₅	2	3	1
	576	TE ₂₆	1	2.5	0.5

¹⁾ Communications & Power Industries; formerly VARIAN

Table XIII: 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	Power [MW]	Efficiency [%]	Pulse length [μ s]	
IAP, Nizhny Novgorod [51,52]	250	TE _{20,2}	0.3	31	30 - 80	
	350		0.13	17	30 - 80	
	430		0.08	10	30 - 80	
	500	TE _{28,3}	0.1	8.2	30 - 80	
	540		0.06	6	30 - 80	
	600	TE _{38,2}	0.05	5	30 - 80	
	650		0.04	4	40	
MIT, Cambridge [38,264,314-318]	113.2	TE _{23,6}	0.84	25	3	
	113.2	TE _{23,6} /TEM ₀₀	0.84	17	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	
UNIVERSITY, Fukui [280,285]	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 10-100 W) step tunable, mm- and sub-mm wave source in the frequency range from 38 GHz (fundamental) to 889 GHz (TE_{8,6} mode, 2nd harmonic) [53-56,306-313,319,320].

Institution	Frequency [GHz]	Mode	Voltage [kV]	Current [A]	Power [MW]	Efficiency [%]	
MIT, Cambridge [315]	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 [315]) 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 [315]	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 [315]) 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 [10,15,302]	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 [27-29,129-132] Palo Alto, Toki	84	TE _{15,3}	TEM ₀₀	50	14	80	cryo. mag.
GYCOM/IAP Nizhny Novgorod, [1,11,40,57-60,62-65, 134, 215,216,321-328]	15	TE ₀₁	TE ₀₁	4	50	15	roomtemp.
	24.1 (2Ω _c)	TE ₁₁	TE ₁₁	3.5	23	12	roomtemp.
	24.15	TE ₃₂	TE ₃₂	36	50	33	roomtemp.
	23 (2Ω _c)	TE ₁₂	TE ₁₂	13	50	25	roomtemp.
	30 (2Ω _c)	TE ₀₂	TE ₀₂	28	32	25	roomtemp.
				10	42	26	roomtemp.
	30 (2Ω _c)	TE ₀₂	TE ₀₂	30	35	26	roomtemp.
				12	24	25	PM, 68 kg ²⁾
	28.25 (2Ω _c)	TE ₁₂	TE ₁₂	12	24	25	PM, 68 kg ²⁾
	31.8-34.8	TE ₁₁	TE ₁₁	1.2	40	12	mech. tun.
	35.5-37.5	TE ₀₁	TE ₀₁	0.5	15.3	16	mech. tun.
	35.15	TE ₀₂	TE ₀₂	9.7	43	25	cryo. mag.
	35	TE ₀₂	TEM ₀₀	10-40	30-40	25-30	cryo. mag.
	37.5	TE ₆₂	TEM ₀₀	20	35	30	cryo. mag.
	68-72	TE ₁₃	TE ₁₃	1.4	22	17.5	mech. tun.
	83	TE ₉₃	TEM ₀₀	10-40	30-40	25-30	cryo. mag.
150	TE ₀₃	TE ₀₃	22	30	40	cryo. mag.	
160 (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)			1	5	20	cryo. mag.	
326 (2Ω _c)			1.5	6	20	cryo. mag.	
mitsubishi, Amagasaki [61,329-331]	28 (2Ω _c)	TE ₀₂	TE ₀₂	10	38.7	21	PM, 600 kg ²⁾ tapered B

¹⁾ Communications & Power Industries, formerly VARIAN

²⁾ PM: permanent magnet

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

9 Relativistic Gyrotrons

Institution	Frequency [GHz]	Mode	Voltage [MV]	Current [kA]	Power [MW]	Efficiency [%]	Type
IAP, Nizhny Novgorod [332-334]	9.23	TE ₀₁	0.27 (0.28)	0.12 (0.06)	10 (7.0)	32 (55)	slotted echelette cavity, n = 3-10
	20	TM ₀₁	0.5	0.7	40	11.4	
	79-107	TM _{1n}	0.5	2-6.5	30	3-1	
IAP, Nizhny Novgorod Lebedev/General Phys. Inst. Moscow [333,335-337]	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 [338]	12	TE ₁₃	0.12	8.0	60	6.3	plasma filled slotted cavity
UNIV. Michigan [339-345]	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
					40		unslotted cavity
				20		unsl. noncoax. cavity	
	10	TE ₁₁	0.4	0.025	0.6	6	
NRL, Washington D.C. [346-349]	8.35-13	4-5 modes	3.3	80	1000	0.4	superradiant
			0.78	1.6 (3.5)	100	8 (4) ^{*)}	
	35	TE ₆₂	1.15	2.5	275	10	
	35	TE ₁₃	0.9	0.65	35	6	slotted cavity
Tomsk Polytech. Inst. [350]	3.1		0.75	8.0 (30)	1800	8	also viricator interaction
UNIV. Niigata [351]	18.2	TE ₀₁	0.08	0.5	0.2	0.55	
UNIV. Strathclyde [352-355]	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 [356-359]	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	0.01	0.085	3.4
	130.3	TE ₄₂	4	0.25	0.01	0.1	4.0

Table XIX: Relativistic large orbit harmonic pulse gyrotrons with axis-encircling electron beam ($\tau = 10 \mu\text{s}$). The 115 and 130 GHz experiments employed a quasi-Pierce type thermionic gun ($\tau = 10 \mu\text{s}$).

10 Quasi-Optical Gyrotrons

Institution	Frequency [GHz]	Mode resonator	Power [kW]	Efficiency [%]	Pulse length [ms]	Type
ABB, Baden [90,123]	92	TEM _{00q}	90	10	10	
CRPP, Lausanne [36,37,90,360]	90.8	TEM _{00q}	150	15	5	
	100	TEM _{00q}	90	15	15	
	200 (2Ω _c)	TEM _{00q}	8	3.5	15	
IAP, Nizhny Novgorod [361]	100	TE ₀₆₁	260	6.5	0.04	echelette cavity
MIT, Cambridge [362,363]	136	HE ₀₆₁ ⁰	83	18	0.003	confocal
	114.3	HE ₀₅₁ ⁰	75	16	0.003	slot-cavity
Moscow-State UNIV. [364]	35	TEM _{00q}	1	15	CW	
	95	TEM _{00q}	1	15	CW	
NRL, Washington D.C. [266,365,366]	110	TEM _{00q}	80	8	0.013	
	115	TEM _{00q}	431	12.7 (SDC)	0.013	
			197	16.1 (SDC)	0.013	
	120	TEM _{00q}	600	9	0.013	
			200	12	0.013	
TOSHIBA, Otawara [147]	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 [356,357,367-376]	125	TE ₄₁	10	2	-	0.9	0.5	1.0	oscillator
LLNL Livermore [377]	220	TE ₁₁	50	2.5	-	3.0	2.0	1.0	oscillator
MIT Cambridge [92,378,379]	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 [380,381]	15	TE ₁₁	7	1.5	-	0.45	0.4	1.2	oscillator
UNIV. Strathclyde [382-384]	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 [93]	9.5	TM ₀₁	35	3.5	-	1.15	0.4	2.5	oscillator corr.w.g.
Tomsk Polytechn. Inst. [94]	25		20	0.2	-	0.64	0.9	14	oscillator diel.w.g.
UNIV. Niigata, NIFS, UNIV. Maryland [95]	19.5	TM ₀₁	0.2	3.8	-	0.9	0.035	0.15	oscillator corr.w.g.
UNIV. Yale, NRL, Washington D.C. [96]	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 Gyrokystrons, Gyro-TWT's, Gyrotwystrons, Gyro-BWOs and other Gyro-Devices

- Weakly Relativistic Pulse Gyrokystrons

Institution	Frequency [GHz]	Mode	No. of cavities	Power [kW]	Efficiency [%]	Gain [dB]	BW [%]	Type
CPI ¹⁾ , Palo Alto [15,88]	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. [385-390]	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 [391,392]	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 [391-405]	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
		TE ₀₁	4	280	32	34	0.53	
	35.12 ($2\Omega_c$)	TE ₀₂	2	258	18	17	0.3	tapered B-field
		TE ₀₂	2	300	22		0.3	2-cav. gyrotron
	93.2	TE ₀₁		230	30		0.3	2-cav. gyrotron
			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
	Kwangwoon Univ., Seoul [406]	27.85	TE ₀₁	5	150	26	50	0.1
NRL, Washington D.C. [72-74,88,266,407-418]	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		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

- Weakly Relativistic CW Gyrokystrons

Institution	Frequency [GHz]	Mode	No. of cavities	Power [kW]	Efficiency [%]	Gain [dB]	BW [%]	Type
CPI, Litton, NRL, U.M. [72-74,385-390]	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 [395]	9.17	TE ₁₁	2	0.7	70	22	0.3	
IAP/ISTOK Moscow [396,399]	91.6	TE ₀₁	4	2.5	25	31	0.36	

QOGK: Quasi-optical Gyrokystron;

SDC: Single-stage Depressed Collector

¹⁾ Communications & Power Industries, formerly VARIAN

Table XXIII: Weakly relativistic gyrokystron experimental results.

Institution	Frequency [GHz]	Mode	No. of cavities	Power [MW]	Efficiency [%]	Gain [dB]	BW [%]	Type
UNIV. Maryland [66-68,419-429]	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
			3	27	13	25	0.1	coaxial
	17.14 (2Ω _C)	TE ₀₂	3	27	13	25	0.1	coaxial
			4	18.5	7.3	24	0.35	coaxial
19.75 (2Ω _C)	TE ₀₂	2	32	29	27	0.1		
29.57 (3Ω _C)	TE ₀₃	2	1.8	2.0	14	0.1		

Table XXIV: Relativistic pulse gyrokylystron experimental results.

Institution	Frequency [GHz]	Mode	Power [kW]	Efficiency [%]	Gain [dB]	Bandwidth [%]	Type
CPI ¹⁾ , Palo Alto [15,88,430,431]	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
IAP, Nizhny Novgorod [432-435]	36.3	TE ₋₂₁ /TE ₊₁₁	180	27	25	10	cuspl. gun with axis-encircl. beam
MIT, Cambridge [436,437]	140	HE ₀₆₁ ⁰	30	12	29	1.6	quasi-optical
NRL, Washington D.C. [88,438-441]	32.5	TE ₁₀	6.3	10	16.7	33	1-stage tapered
	35.5	TE ₁₀	8	16	25	20	2-stage tapered
	32.3	TE ₁₀	50	28	25	11	folded waveguide axis-encircl. beam
	34.0	TE ₀₁	137	17	47	3.3	2-stage output
	35.6	TE ₁₁	60	13.5	60	11	2-stage output
UCLA Los Angeles [442-450]	9.3	TE ₁₀	55	11	27	11	diel. coat. waveg. axis-encircl. beam
	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
UNIV. Hsinchu [98,451-455]	35.8	TE ₁₁	18.4	18.6	18	10	
	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)
UNIV. Tel Aviv [456]	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 [99,433,435,457-461]	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 [462]	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. *) [463,464]	35	TE ₁₁	20	11	30		explosive-emission gun, bifilar helical wiggler

*) 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	output w.g.	Power [kW]	Efficiency [%]	Gain [dB]	BW [%]
CPI ¹⁾ , Palo Alto [73,465]	94	TE ₀₁ (4 cav.)	TE ₀₁	59	14.9	35	1.6
NRL, Washington D.C. [466]	4.5	TE ₁₀	TE ₁₀	73	22.5	37	1.5
	31.5	TE ₄₂ ($2\Omega_c$)	TE ₄₂	160	25	30	1.3
	93.5	TE ₀₁ (3 cav.)	TE ₀₁	48	17.5	30	2.0
IAP, N.Novgorod, NRL Washington D.C. [467,468]	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/Gyrotrotion

Institution	Frequency [GHz]	Mode cavity	output w.g.	Power [kW]	Efficiency [%]	Gain [dB]	BW [%]
NRL, Washington D.C. [100,469-474]	31.8	TE ₂₂	TE ₄₂ ($2\Omega_c$)	100	20	30	1.3
	33.7	TE ₀₂	TE ₀₃ ($2\Omega_c$)	430	35	30	0.3
	34.6	TE ₀₂	TE ₀₃ ($2\Omega_c$)	180	32	30	3.0
	32.5	TE ₀₂	TE ₀₃ ($2\Omega_c$)	200	12	36	3.0
	35	TE ₀₂ /TE ₀₃ ($2\Omega_c$)	TE ₀₄ ($2\Omega_c$)	110	32	53	3.0
	33.75	Gyrotrotion		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	output w.g.	Power [MW]	Efficiency [%]	Gain [dB]	BW [%]
UNIV. Maryland [475]	9.878	TE ₀₁	TE ₀₁	21.6	21	25.5	
	19.76	TE ₀₁ (9.88GHz)	TE ₀₂ ($2\Omega_c$)	12	11	21	

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

- Weakly Relativistic Pulse Gyro-BWOs

Institution	Frequency [GHz]	Mode	Power [kW]	Efficiency [%]	Bandwidth [%]	Type
IAP, N. Novgorod FZK, Karlsruhe [434,435]	24.5	TE ₋₂₁ /TE ₁₁	5.5	5	6	MIG
IAP, Nizhny Novgorod [433]	35-38	TE ₋₂₁ /TE ₁₁	34	7	15	quasi-Pierce gun with kicker
MIT, Cambridge, LLNL, Livermore [476]	140	TE ₁₂ ^c	2	2	9	
NRL, Washington D.C. [477]	27.8	TE ₁₀ ^r	2	9	3	electr. tuning
UNIV. Hsinchu [478-480]	29.2	TE ₁₀ ^r	6	15	13	magn. tuning
	33.5	TE ₁₁ ^c	20-67	6.5-21.7	5	injection locked
			100	25		free running
			154	39	1	injection locked
			164	41	1	inverse injec. locked
UNIV. Utah [481]	10	TE ₁₀ ^r	0.72	10	8	

r = rectangular waveguide; c = circular waveguide

- 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 [482,483]	10	TM ₁₁	200	22		0.45	2	Cherenkov with cycl. mode selection
	35(2 Ω c)	TE ₋₂₁ / TE ₊₁₁	1.15	10	15(Δ B)	0.35	0.032	hel. w.g. with Δ m=3 perturb.
UNIV. Kanazawa [484,485]	9-13	TE ₁₀ ^r	1	0.75 (0.02)	1	0.45	0.3(10)	
UNIV. Michigan [486,487]	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 [488,489]	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
UNIV. Tohoku, Sendai [490-498]	10.0	TE ₁₁ ^r	TE ₁₁ ^r	10	36	0.02	magnetron-type cavity
	10.5 (2Ω _c)	TE ₃₁ ^c	TE ₃₁ ^c	0.7	10		
				1.3	7		
	30.3 (3Ω _c)	TE ₄₁ ^c	TE ₀₁ ^c	6.9	35 (75 electr.)	44(SDC) (92 electr.)	
				6.9			
100 (10Ω _c)	TE _{11,1} ^c	TE ₀₁ ^c	0.32	1.7 (5 electr.)	25	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 (3Ω _c)	TE ₀₂	8	6.75	0.2
Toshiba, Otawara	140 (3Ω _c)	TE ₀₃	8	1	1
UNIV. Fukui [499]					

Table XXX: Experimental results of gyropeniotrons.

Institution	Frequency [GHz]	No. of Cavities	Voltage [MW]	Current [A]	Power [MW]	Efficiency [%]	Gain [dB]	Pulse length [μs]
BINP, Novosibirsk [102,500-503]	0.915	3	0.3	12	2.6	73	30	30
	7.01 (2Ω _c)	5	0.427	230	55	56	72	1.1
NRL, Washington D.C. [504-506]	11.43 (2Ω _c)	7	0.48	210	25	25	55	0.2
					15	15	55	1.2

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 [507-516]	3	0.11	120	TE ₁₁ ^c	40	2.3		2.2	0.8	Ind. LINAC	0.025	spon.emiss.
	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 [517-519]	24	0.05/0.04	34/23	TE ₁₁ ^o /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 [520]	100	0.1	20	TE ₀₂ ^c	1	2		0.5	0.15	Pulse Line	0.03	spon.emiss.
ENEA Frascati [521-523]	85-150	0.61	25	TE ₀₁ ^r	0.0015	0.19		2.3	0.00035	Microtron	5.5	oscillator
EP Palaiseau [524]	120	0.03	20	TE ₁₁ ^c	11.5	6.4		0.6	0.3	Electrostatic	0.02	superrad.
FOM Nieuwegein [108-117,525]	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 [106]	2.6	0.04	74.2	TE ₀₁ ^r	1.2	10	6	0.17	0.07	Modulator	5.0	amplifier
Palo Alto [106]	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
	54	0.2	3.18	TE ₀₁ ^c	0.15	6	10(30)	0.07	0.037	Modulator	4.0	amplifier
IEE,China [118]	35	0.31	110		140	5.2	57	3.4	0.95	Ind. LINAC	0.05	amplifier
IAP, Nizhny Novgorod [526-528]	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. [529-535]	75	0.10	40	TEM	100	4.2		0.8	3.0	Pulse Line	1.0	oscillator
IAP/U. Strath./HERC [536-538]	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. [539-547]	29.3	0.11	60	TE ₁₁ ^c	6	5(4)		0.8	0.15(0.2)	Ind. LINAC	0.2	oscillator
	30.74	0.12	60	TM ₁₁ ^c /TE ₁₁ ^c	48	35(30)		0.8	0.17(0.2)	Ind. LINAC	0.15	oscillator
	38.2	0.06	60	TM ₁₂ ^c /TE ₁₁ ^c	3	3(2)		0.8	0.15(0.2)	Ind. LINAC	0.2	oscillator
	35	0.19	72	TE ₁₁ ^c	30	10		1.5	0.2	Ind. LINAC	0.2	amplifier
ILE Osaka [548]	250	0.05	30	TE ₁₁ ^c	0.6	0.5	110	0.6	0.2	Ind. LINAC	0.04	amplifier
ILT/ILE Osaka [549]	60-110	0.71	60	TE ₀₁ ^r	0.01	0.2		9.0	0.05	RF LINAC	4x10 ⁻⁶	oscillator
ISAS, Sagami-hara [550]	11.8	0.09	32.7	TM ₈₁ ^c	3	1		0.43	0.19	Pulse Line	0.4	oscillator
JAERI, Ibaraki [551,552]	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 [553-555]	27	0.13	32	TM ₁₁ ^c	0.001	0.15		0.4	0.0017	Electrostatic	10-30	oscillator
KEK, Tsukuba [556-560]	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 [561]	11.2/16.4			TM _{02,03}	5	0.125		0.8	5.0	Modulator	1.0	oscil./ampl.
LLNL, Livermore [78,562-566]	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)						

Institution	Frequency [GHz]	B _w [T]	λ _w [mm]	Mode	Power [MW]	Efficiency [%]	Gain [dB]	Voltage [MV]	Current [kA]	Accelerator	Pulse-Length [μs]	Type
MIT, Cambridge [378,567-570]	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. [571,572]	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. [118]	95	0.2	100		10	4		2.5	0.1	Pulse Line	0.25	oscillator
RI, Moscow [573]	6-25	0.03	48	TE ₁₁ ^c /TM ₀₁ ^c	10	1.7		0.6	1	Pulse Line	2	spon. emiss.
SIAE, Chengdu [574]	37	0.125	34.5	TE ₁₁ ^c	7.6	5.4		0.5	0.28	Electrostatic	0.015	oscillator
SIOFM, Shanghai [575,576]	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 [577]	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 [578,579]	90	Smith-Purcell		TEM ₀₀	0.03	0.03		0.46	0.2	Pulse Line	0.015	oscillator
UNIV. Liverpool [119]	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 [561,580,581]	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 [582]	120-880	0.15	71.4		0.027	0.5		2-6	0.002	Electrostatic	1-20	oscillator
UNIV. Strathclyde [583-585]	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 [586-588]	32.5	0.13	23	TE ₁₁ ^c	0.5	5.0		0.3	0.03	Pulse Line	0.1	oscillator
UNIV. Tel-Aviv [589-593]	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 ^(l)	0.01	0.7(0.5)		1.1-1.5	0.001(0.0014)	Electrostatic	30000	oscillator
UNIV. Twente [594]	35	0.19	30	TE ₁₁ ^c /TM ₀₁ ^c	2.3	0.6		0.5	0.75	Pulse Line	0.1	spon. emiss.

r: rectangular waveguide;

c: circular waveguide

Table 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 [108-117,525]. The project was terminated in the autumn of 2001.

14 Comparison of Gyrotron and FEM for Nuclear Fusion

Table XXXIV lists a comparison of the main performance parameters and features of gyrotron oscillators and FEMs for ECRH of plasmas in nuclear fusion research. The important advantage of the FEM is its 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 millimeter wave source which has had an extensive on-the-field experience during fusion plasma heating experiments over a wide range of frequencies and power levels (8-170 GHz, 0.1-1.0 MW) [16].

	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 - 650 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	cutoff cavity 2 kW/cm ²	oversized circuit far away from cutoff
7. Power density in cavity	high	low
8. Longitudinal mode competition in cavity	single mode operation	nonlinear temporal dynamics can bring broad frequency spectrum
9. Linearly polarized output mode	generated by internal quasi-optical mode converter	linearly polarized, low-order resonator mode
10. Number of internal quasi-optical mirrors	2-4 on ground potential 0.9% ohmic losses	15 - 25 phase coherence required mostly on 2 MW potential 6% ohmic losses
11. Absorbed power on first mirror (1 MW, 140 GHz)	3 kW	12 kW
12. Internal microwave diagnostics	not required	required
13. Output power (140 GHz) present status	high average power 1 MW / 12 s 0.9 MW / 180 s (coax. 2.2 MW / 17 ms)	2 GW/20ns but very low duty cycle (LLNL amplifier)
14. Exp. system efficiency without energy recovery	high 35%	low 5 - 10%
15. Collector loading	relatively low	high
16. Theor. system efficiency with depressed collector	60% (exp. 50%)	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 (140 GHz)	1 MW (coax., 4 MW)	5 MW

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

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