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**State-of-the-Art of  
High Power Gyro-Devices  
and Free Electron Masers  
Update 2001**

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**STATE-OF-THE-ART OF HIGH POWER GYRO-DEVICES  
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 0.5-1.0 MW gyrotrons is 5 s at 110 GHz and 10 s at 140 GHz and 170 GHz, with efficiencies slightly above 30%. The energy world record of 90 MJ (0.64 MW at 140 s pulse length and 140 GHz) has been achieved by the European FZK-CRPP-TED-CEA collaboration. Total efficiencies around 50 % have been obtained using single-stage depressed collectors. Diagnostic gyrotrons deliver  $P_{\text{out}} = 40 \text{ kW}$  with  $\tau = 40 \mu\text{s}$  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:  $f \geq 24 \text{ GHz}$ ,  $P_{\text{out}} = 10\text{-}50 \text{ kW}$ , CW,  $\eta \geq 30\%$ . This paper gives an update of the experimental achievements related to the development of high power gyrotron oscillators for long pulse or CW operation and pulsed diagnostic gyrotrons. In addition, this work gives a short overview of the present development 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 ( $3.1 \mu\text{m}$ ) FEL at the Thomas Jefferson National Accelerator Facility obtained a record average power of 1.72 kW.

# STATUS DER ENTWICKLUNG VON HOCHLEISTUNGS-GYRO-RÖHREN UND FREI-ELEKTRONEN-MASERN STAND: ENDE 2001

## 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 0.5-1.0 MW Gyrotrons ist 5 s bei 110 GHz und 10 s bei 140 GHz und 170 GHz, mit Wirkungsgraden wenig über 30%. Der Energieweltrekord von 90 MJ (0.64 MW mit 140s Pulslänge bei 140 GHz) wird von der Europäischen FZK-CRPP-TED-CEA-Zusammenarbeitsgemeinschaft gehalten. Durch den Einsatz von Kollektoren mit einstufiger Gegenspannung werden Gesamtwirkungsgrade um 50% erreicht. Gyrotrons zur Plasmadiagnostik arbeiten bei Frequenzen bis zu 650 GHz bei  $P_{\text{out}} = 40 \text{ kW}$  und  $\tau = 40 \mu\text{s}$  ( $\eta \geq 4\%$ ). Gyrotronoszillatoren finden jedoch auch in der Materialprozeßtechnik erfolgreich Verwendung. Dabei werden Röhren mit folgenden Parametern eingesetzt:  $f \geq 24 \text{ GHz}$ ,  $P_{\text{out}} = 10\text{-}50 \text{ kW}$ , CW,  $\eta \geq 30\%$ . In diesem Beitrag wird auf den aktuellen experimentellen Stand bei der Entwicklung von Hochleistungs-Gyrotronoszillatoren für Langpuls- und Dauerstrichbetrieb sowie von gepulsten Diagnostikgyrotrons eingegangen. Außerdem wird auch kurz über den neuesten Stand der Entwicklung von Gyrotrons mit koaxialem Resonator, Gyrotrons für technologische Anwendungen, relativistischen Gyrotrons, quasi-optischen Gyrotrons, Zyklotron-Autoresonanz-Masern (CARMs) mit schneller oder langsamer Welle, Gyroklystrons, Gyro-TWT-Verstärkern, Gyrotwystron-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 ( $3.1 \mu\text{m}$ ) FEL der Thomas Jefferson National Accelerator Facility erreichte eine Rekord-Durchschnitts-Leistung von 1.72 kW

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
<b>2</b>	<b>Classification of Fast-Wave Microwave Sources</b>	<b>2</b>
<b>3</b>	<b>Dispersion Diagrams of Fast Cyclotron Mode Interaction</b>	<b>3</b>
3.1	Gyrotron Oscillator and Gyroklystron Amplifier	4
3.2	Cyclotron Autoresonance Maser (CARM)	7
3.3	Gyro-TWT (Travelling Wave Tube) and Gyrotwystron Amplifier	9
3.4	Gyro-BWO (Backward Wave Oscillator)	10
3.5	Overview on Gyro-Devices	11
<b>4</b>	<b>Magnicons and Gyroharmonic Converters</b>	<b>12</b>
<b>5</b>	<b>Principle of Free Electron Lasers</b>	<b>14</b>
<b>6</b>	<b>Gyrotron Oscillators and Microwave Vacuum Windows for Plasma Heating</b>	<b>15</b>
<b>7</b>	<b>Very High Frequency Gyrotron Oscillators</b>	<b>26</b>
<b>8</b>	<b>Gyrotrons for Technological Applications</b>	<b>29</b>
<b>9</b>	<b>Relativistic Gyrotrons</b>	<b>30</b>
<b>10</b>	<b>Quasi-Optical Gyrotrons</b>	<b>31</b>
<b>11</b>	<b>Cyclotron Autoresonance Masers (CARMs)</b>	<b>32</b>
<b>12</b>	<b>Gyroklystrons, Gyro-TWTs, Gyrotwystrons, Gyro-BWOs and other Gyro-Devices</b>	<b>33</b>
<b>13</b>	<b>Free Electron Masers (FEMs)</b>	<b>38</b>
<b>14</b>	<b>Comparison of Gyrotron and FEM for Nuclear Fusion</b>	<b>41</b>
	<b>Acknowledgments</b>	<b>42</b>
	<b>References</b>	<b>43-79</b>

## 1 Introduction

The possible applications of gyrotron oscillators and other cyclotron-resonance maser (CRM) fast-wave devices span a wide range of technologies [1-3]. 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) [4-14] 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 MW.

ECRH has become a well-established heating method for both tokamaks [15-20] and stellarators [21-26]. 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 [16,24,27-30]. This suggests that mm-wave gyrotrons that generate output power of at least 1 MW, CW, per unit are required. Since efficient ECRH needs axisymmetric, narrow, pencil-like mm-wave beams with well defined polarization (linear or elliptical), single-mode gyrotron emission is necessary in order to generate a TEM<sub>00</sub> 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 [31,32]. Frequency tuning has been shown to be possible on quasi-optical Fabry-Perot cavity gyrotrons [33,34] as well as on cylindrical cavity gyrotrons with step tuning (different operating cavity modes) [35-43].

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 [44,45] (Tables II-XII) but also refers to the development of very high frequency gyromonotrons for active plasma diagnostics [46-51] (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 [1-3,52-55]. 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 [56-60]. 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,  $\tau = 0.2$   $\mu\text{s}$  and characteristics that will allow approximately 1000 pulses per second will be necessary as drivers [61-63]. 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 [64-67]. 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 [3,27-30] and in the KfK Report 5235 (October 1993) and the FZKA Reports 5564 (April 1995), 5728 (March 1996), 5877 (February 1997), 6060 (February 1998), 6224 (January 1999), 6418 (February 2000) and 6588 (March 2001) with the same title.

## 2 Classification of Fast-Wave Microwave Sources

Fast-wave devices in which the phase velocity  $v_{\text{ph}}$  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 [13,68]

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

here  $\omega$  and  $k_z$  are the wave angular frequency and characteristic axial wavenumber, respectively,  $v_z$  is the translational electron drift velocity,  $\Omega$  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  $\Omega$  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,  $\gamma$  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  $\Omega_b$  (bounce frequency) of the moving charges is proportional to the ratio of the electron beam velocity  $v_z$  to the wiggler field spatial period  $\lambda_w$ . 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 [69-73], 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  $2\pi$  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 [4,74]: Richard Twiss in Australia [75], Jürgen Schneider in the US [76] and Andrei Gaponov in Russia [77]. 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 [78]. 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 [4,74]. 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 [79] (where the term "electron cyclotron maser" was apparently coined) and in Russia [80].

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  $\omega$ - $k_z$  plots or Brillouin diagrams [1,81-84], 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<sub>mn</sub> modes) or derivative (TE<sub>mn</sub> 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 [4-12].

Gyrotron oscillators and gyroklystrons are devices which usually utilize only weakly relativistic electron beams ( $< 100$  kV,  $\gamma < 1.2$ ) with high transverse momentum (pitch angle  $\alpha = v_{\perp}/v_z > 1$ ) [83]. The wavevector of the radiation in the cavity is transverse to the direction of the external magnetic field ( $k_{\perp} \gg k_z$ , and the Doppler shift is small) resulting, according to eqs. (1) and (2), in radiation near the electron cyclotron frequency or one of its harmonics:

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

In the case of cylindrical cavity tubes (see Figs. 1 and 2) the operating mode is close to cutoff ( $v_{ph} = \omega/k_z \gg c$ ) and the frequency mismatch  $\omega - s\Omega_c$  is small but positive in order to achieve correct phasing, i.e. keeping the electron bunches in the retarding phase [81-84]. 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  $\gamma$  and  $R_0$ , a mode represented by  $X_{mn}$  and oscillating at frequency  $\omega$  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  $B_0/\gamma$ . Modern high-power high-order volume mode gyrotron oscillators for fusion plasma applications employ an internal quasi-optical mode converter with lateral microwave output [83] 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  $s$ . The predicted efficiencies for gyrotrons operating at higher harmonics ( $s = 2$  and  $3$ ) are comparable with those operating at the fundamental frequency [4-12,81-84]. At low voltages, the number of electron orbits required for



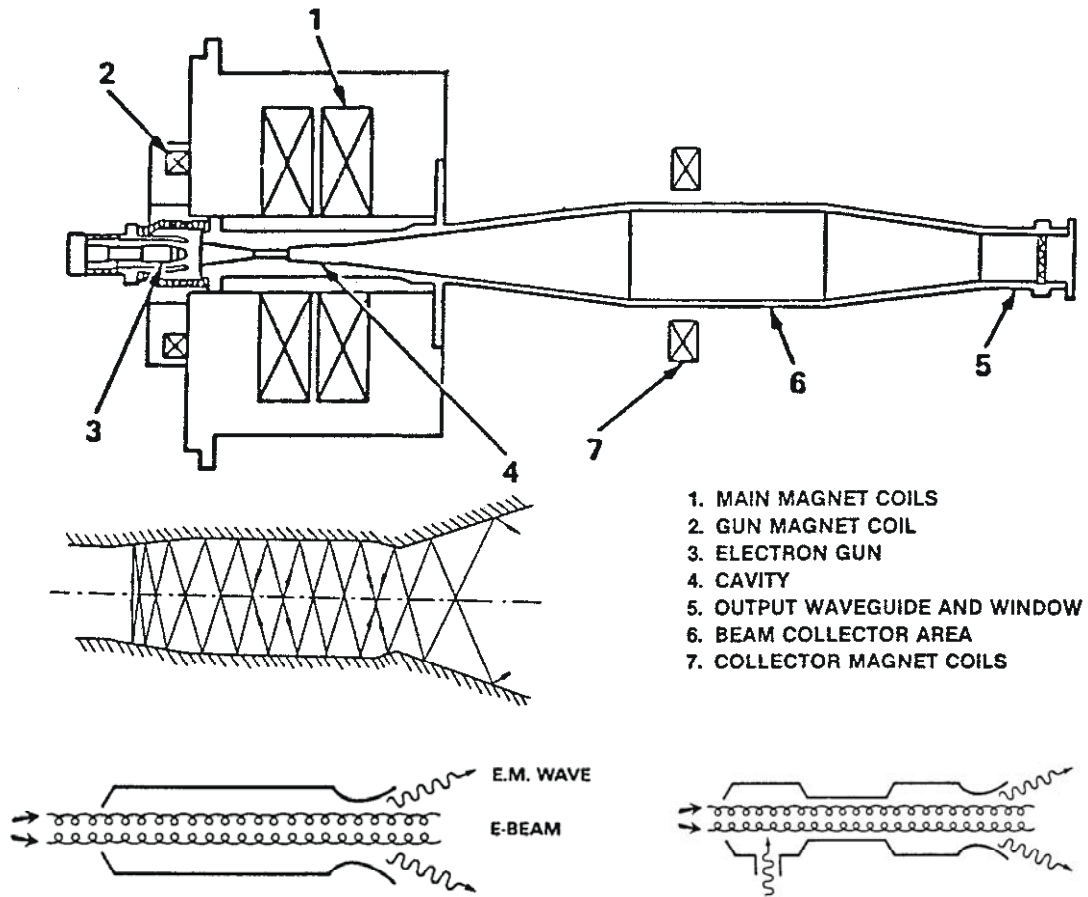


Fig. 1: Schematic of VARIAN CW gyrotron oscillator [9,14] and scheme of irregular waveguide cavities of gyromonotron oscillator (left) and gyrokystron amplifier [81].

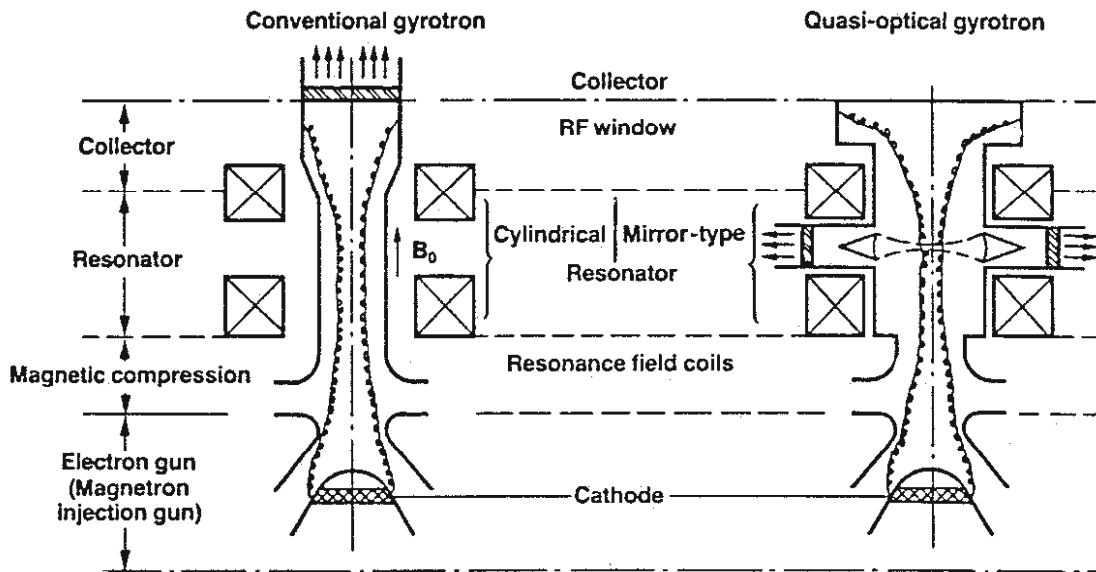


Fig. 2: Principle of a conventional gyrotron with cylindrical resonator and of a quasi-optical gyrotron with mirror resonator [33,34].

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.

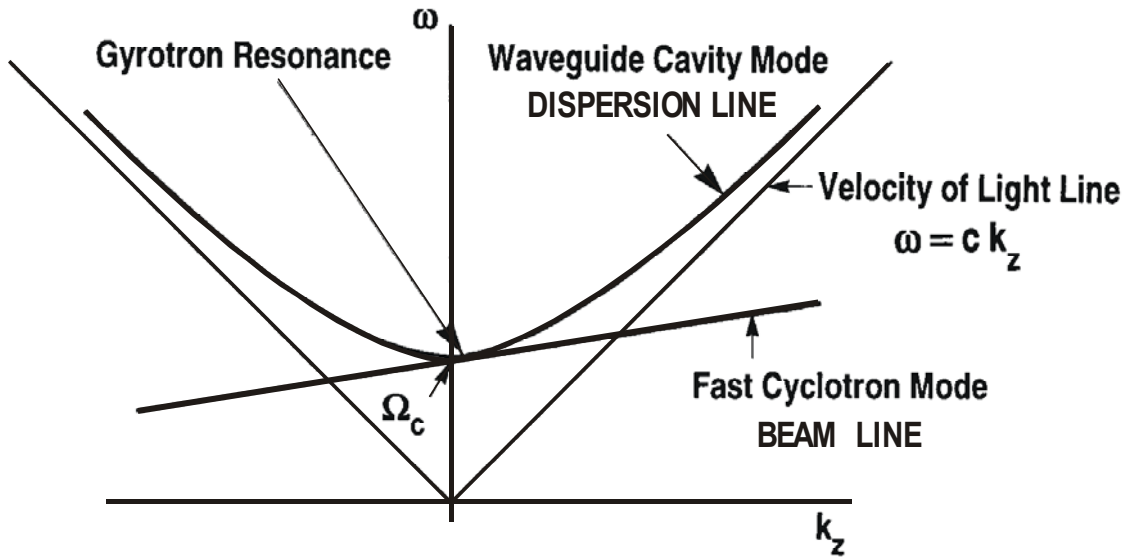


Fig. 3: Dispersion diagram of gyrotron oscillator (fundamental resonance).

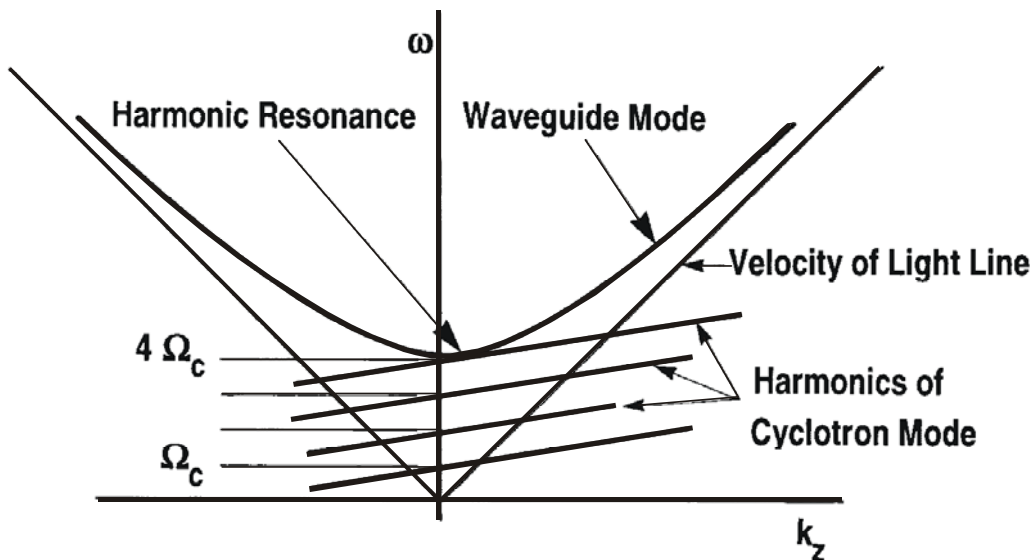


Fig. 4: Dispersion diagram of harmonic frequency gyrotron oscillator.

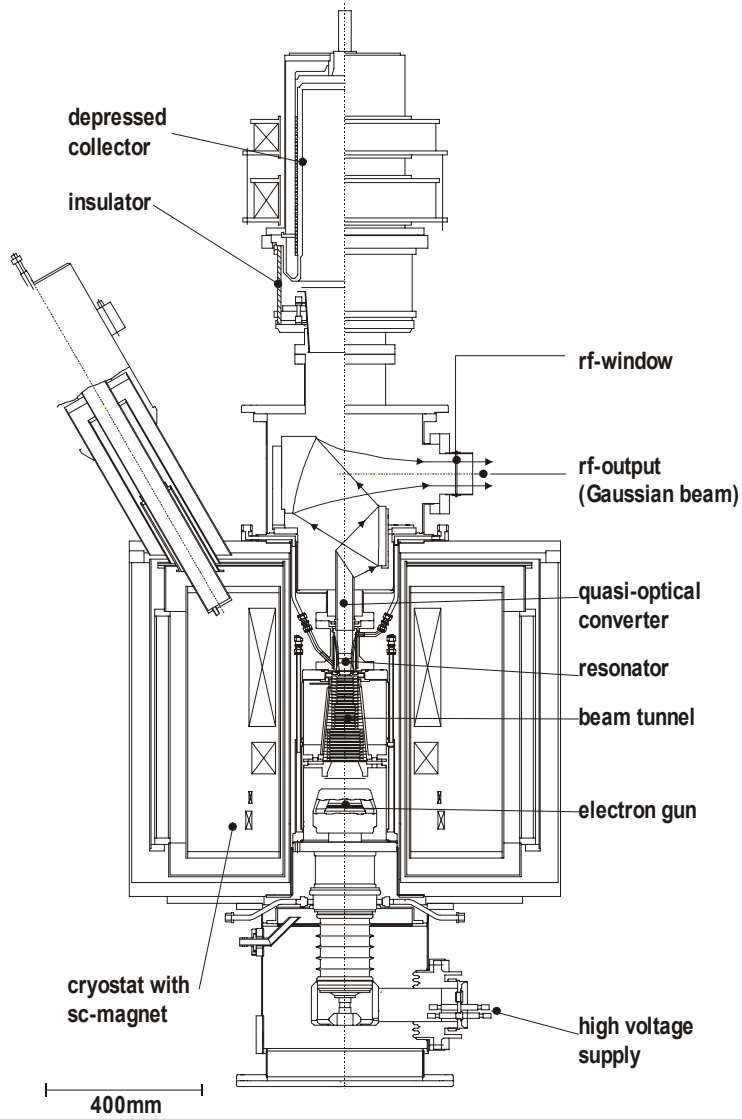


Fig. 5: Schematic layout of modern high-order volume mode gyrotron with quasi-optical mode converter and single-stage depressed collector.

### 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  $\gamma$ ) 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 [13,68]. Fig. 6 shows how

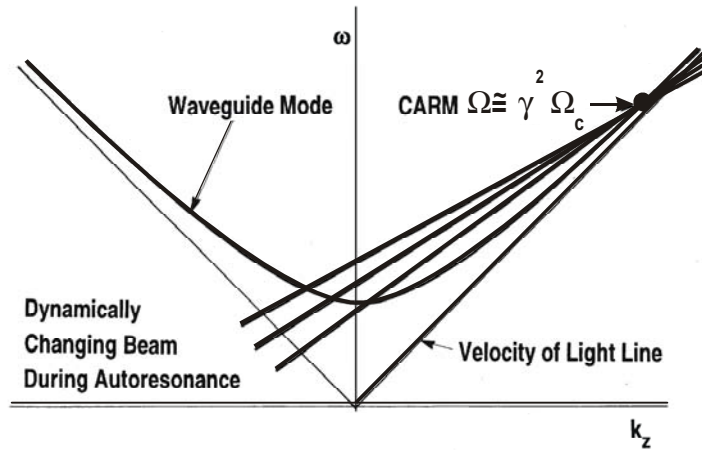


Fig. 6: Dispersion diagram of the cyclotron autoresonance maser (CARM).

the Brillouin diagram of the fast cyclotron wave changes during the autoresonance interaction such that the working frequency  $\omega$  remains constant even though both  $\Omega_c$  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) [68] 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.

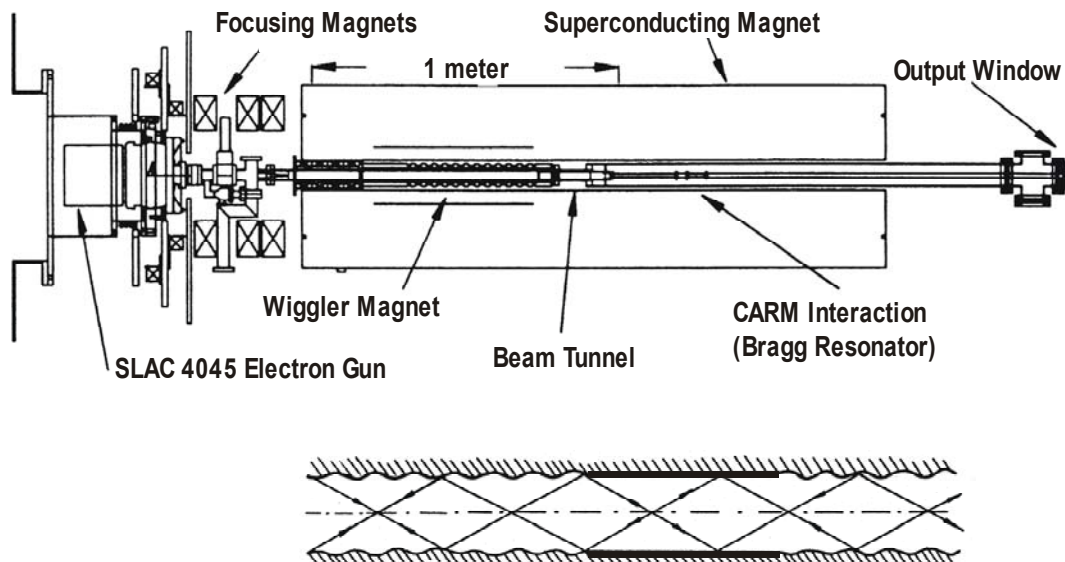


Fig. 7: Schematic of the long-pulse MIT CARM oscillator experiment [85] and scheme of a Bragg resonator [68].

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% [68,85].

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 [86-89], 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

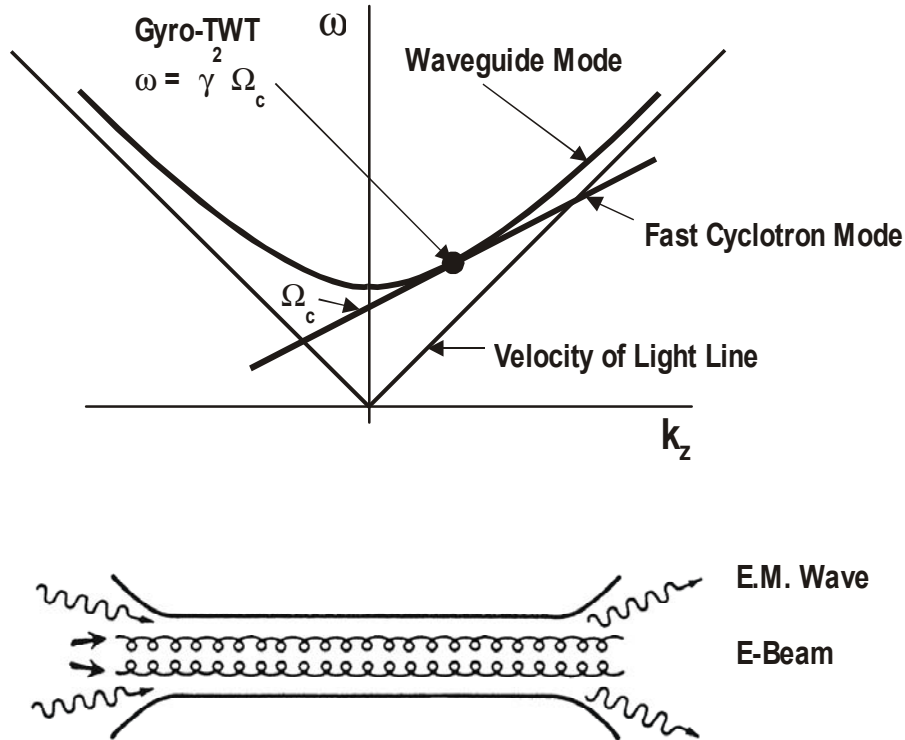


Fig. 8: Dispersion diagram and scheme of interaction circuit of Gyro-TWT amplifier.

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 [90,91].

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 [92].

The gyrotwystron [4], a hybrid device, is derived from the gyrokylystron 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 [93]. 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

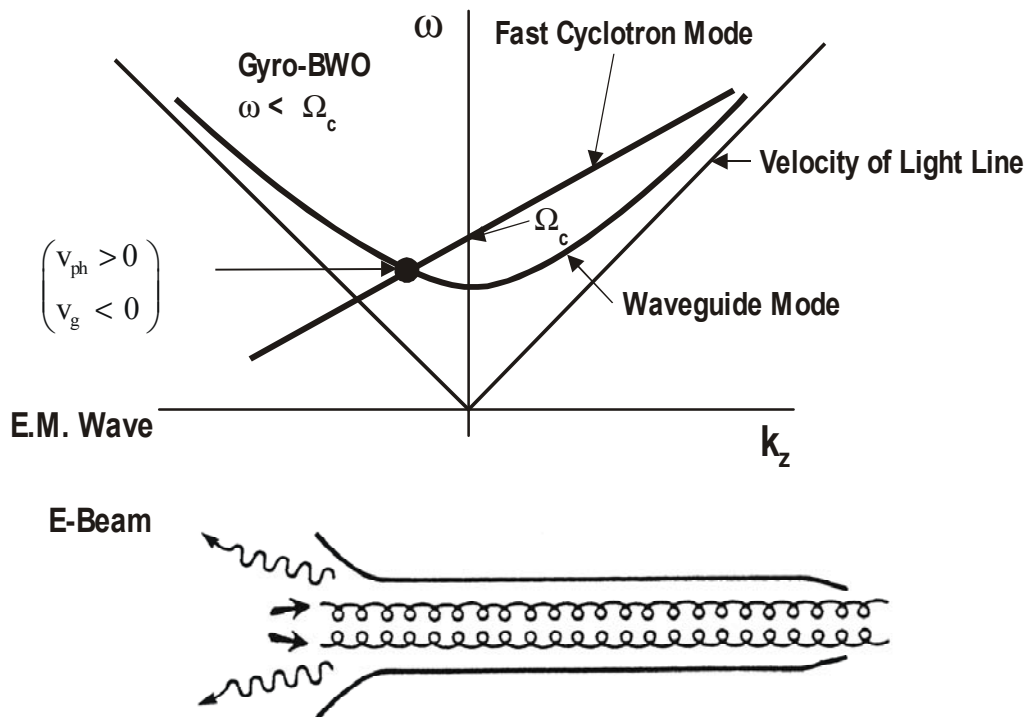


Fig. 9: Dispersion diagram and scheme of interaction circuit of Gyro-BWO.

operation is now governed by the slope of the line, which is a function of  $v_z$ , and thus of the beam acceleration voltage  $U_{\text{beam}}$ . 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

$U_{\text{beam}}$  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 [4]. 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 ( $s=1$ ) [4]. 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.

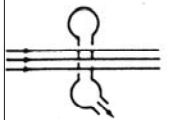
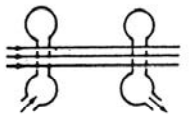


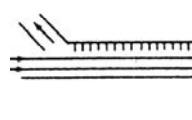
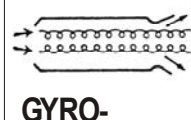
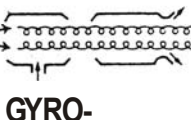
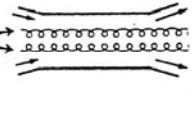
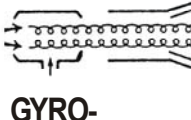
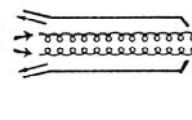

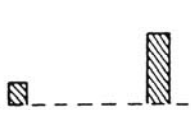
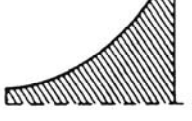


"O" TYP DEVICES	 <b>MONOTRON</b>	 <b>KLYSTRON</b>	 <b>TWT</b>	 <b>TWYSTRON</b>	 <b>BWO</b>
TYPE OF GYROTRON	 <b>GYRO-MONOTRON</b>	 <b>GYRO-KLYSTRON</b>	 <b>GYRO-TWT</b>	 <b>GYRO-TWYSTRON</b>	 <b>GYRO BWO</b>
MODEL RF-FIELD STRUCTURE					
ORBITAL EFFICIENCY	<b>0.42</b>	<b>0.34</b>	<b>0.7</b>	<b>0.6</b>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

Table I: Overview of gyro-devices and comparison with corresponding conventional linear-beam (O-type) devices [4].

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 [81-84,94].

## 4 Magnicons and Gyroharmonic Converters

The magnicon is a member of the class of scanning-beam amplifier tubes [11,95]. It is a magnetized device that uses a fast-wave output cavity. Therefore, it can also be grouped with gyro-devices in which electrons gyrating in an external magnetic field emit bremsstrahlung radiation near the cyclotron resonance. In the earliest version of the magnicon, an electron beam is deflected in the unmagnetized input cavity, using a rotating  $TM_{110}$  mode and after an also unmagnetized drift space, the deflected beam is spun up to high transverse momentum by entry into a strong magnetic field at the entrance of the output cavity.

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

Recently, higher perveance versions of the magnicon have been developed [95], 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  $\omega$  and  $TE_{72}$  mode at frequency  $7\omega$  in a cylindrical waveguide [96]. 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  $\mu$ 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 [96,97].



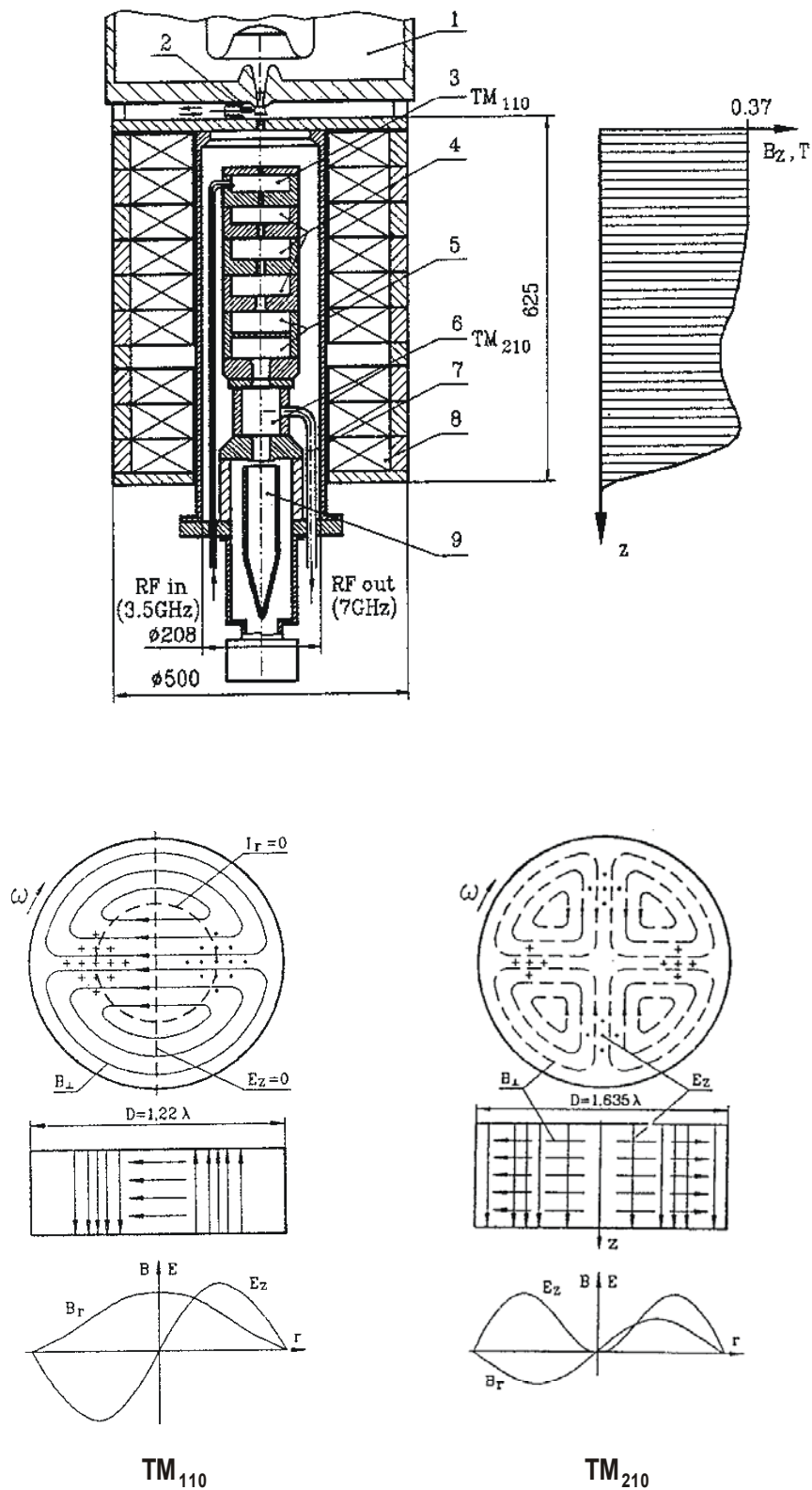


Fig. 10: Schematic layout of the magnicon: 1 - electron source; 2 - vacuum valve; 3 - drive cavity; 4 - gain cavity; 5 - penultimate cavity; 6 - output cavity; 7 - waveguide (x2); 8 - solenoid; 9 - collector [95].

## 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 [69-73,81,82]. To achieve this spectral versatility, FELs exploit relativistic beam technology to upshift the electron "wiggle" frequency by an amount roughly proportional to  $\gamma^2$  (see Fig. 11 and Section 2). In this respect, perhaps a more descriptive name is that coined by R.M. Phillips [98]: 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 [4,13,68]. 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) [99].

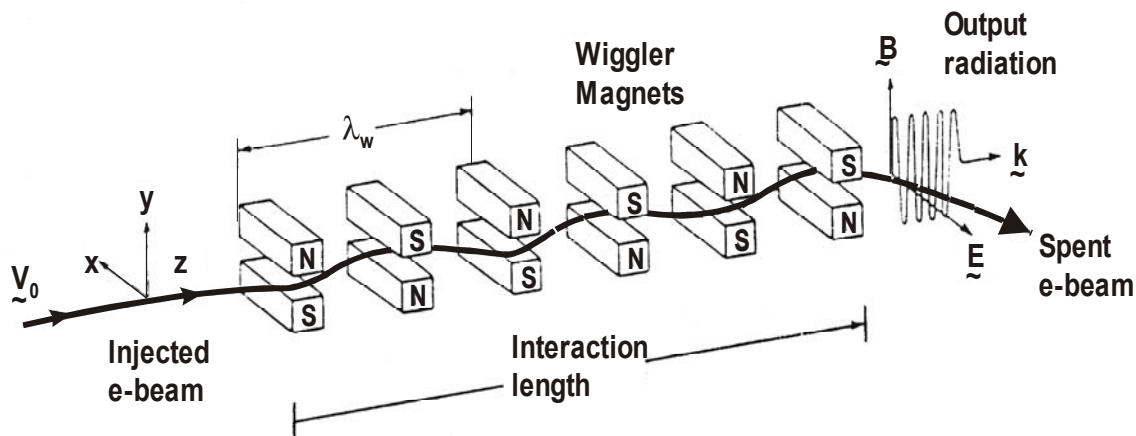


Fig. 11: The basis FEM configuration. Electrons in an injected electron beam undulate in the periodic magnetic field of the wiggler.

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 [100-109]. Rapid tunability over more than  $\pm 5\%$  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 Table XXXII. The highest CW power generated by a FEM is 36 W (15 GHz) [110] whereas the IR (3.1  $\mu\text{m}$ )-FEL at the Thomas Jefferson National Accelerator Facility obtained a record average power of 1.72 kW at 0.8% efficiency [111].

## 6 Gyrotron Oscillators and Microwave Vacuum Windows for Plasma Heating

Institution	Frequency [GHz]	Mode cavity	Mode output	Power [MW]	Efficiency [%]	Pulse length [s]
ABB, Baden [83,112]	8	TE <sub>01</sub>	TE <sub>01</sub>	0.35	35	0.5
	39	TE <sub>02</sub>	TE <sub>02</sub>	0.25	42	0.1
CPI <sup>2)</sup> , Palo Alto [9,14,113-115]	8	TE <sub>21</sub>	TE <sub>10</sub>	0.5	33	1.0
	28	TE <sub>02</sub>	TE <sub>02</sub>	0.34	37	CW
				0.2	45	CW
	35	TE <sub>02</sub>	TE <sub>02</sub>	0.2	35	CW
	53.2,56,60	TE <sub>01/02</sub>	TE <sub>02</sub>	0.23	37	CW
				0.21	36	3
	70.15	TE <sub>10,3</sub>	TEM <sub>00</sub>	0.6	47 (SDC)	2.25
	84	TE <sub>15,2</sub>	TE <sub>15,2/4</sub>	0.5	28	0.1
				0.89	28	0.001
	CPI <sup>2)</sup> , NIFS Palo Alto, Toki [26,116-119]	84	TE <sub>15,3</sub>	TEM <sub>00</sub>	0.5	29
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 [10,36,37,120-122]	28	TE <sub>42</sub>	TEM <sub>00</sub>	0.5	40	0.5
	37.5	TE <sub>62</sub>	TEM <sub>00</sub>	0.5	35	0.1
	53.2	TE <sub>83</sub>	TEM <sub>00</sub>	0.5	40	0.1
				0.3	36	1.0
	70	TE <sub>93</sub>	TEM <sub>00</sub>	0.68	48 (SDC)	3.0
	75	TE <sub>94</sub>	TEM <sub>00</sub>	0.5	37	0.1
	82.5	TE <sub>11,3</sub>	TE <sub>11,3</sub>	1.0	50	0.0001
				1.5	36	0.0001
	82.7	TE <sub>10,4</sub>	TEM <sub>00</sub>	0.65	38	3.0
				0.65	53 (SDC)	3.0
				0.9	32	0.3
	84	TE <sub>12,5</sub>	TEM <sub>00</sub>	0.88	54 (SDC)	3.0
HUGHES, Torrance [81]	60	TE <sub>02</sub>	TE <sub>02</sub>	0.2	35	0.1
IAP, Nizhny Novgorod [123]	25	TE <sub>03</sub> (2 $\Omega_c$ )	TE <sub>03</sub>	0.8	40 (twin e-beam)	0.0001
IECAS, Beijing [124,125]	24.1	TE <sub>01</sub>	TE <sub>01</sub>	0.15	24	0.02
	34.3(2 $\Omega_c$ )	TE <sub>02/03</sub>	TE <sub>03</sub>	0.2	30	0.02
LAP/INPE, Sao Paulo [126]	24.2	TE <sub>12</sub>	TE <sub>12</sub>	0.0058	16	0.000015
	30.4	TE <sub>22</sub>	TE <sub>22</sub>	0.0063	18.5	0.000015
MITSUBISHI, Amagasaki KYOTO UNIV. [127]	88	TE <sub>8,2</sub>	TEM <sub>00</sub>	0.35	29	0.1
NEC, Kawasaki [128]	35	TE <sub>01</sub>	TE <sub>01</sub>	0.1	30	0.001
NRL, Washington D.C. [81,129]	35	TE <sub>01</sub>	TE <sub>01</sub>	0.15	31	0.02
	35	TE <sub>04</sub>	TE <sub>04</sub>	0.475	38	0.001
	35	TE <sub>24</sub>	TE <sub>24</sub>	0.43	40	0.001
PHILIPS <sup>1)</sup> , Hamburg [130]	70	TE <sub>02</sub>	TE <sub>02</sub>	0.14	30	CW
THALES ED <sup>3)</sup> , Velizy [83,131]	8	TE <sub>51</sub>	TE <sub>51</sub>	1.0	45	1.0
	35	TE <sub>02</sub>	TE <sub>02</sub>	0.2	43	0.15
TOSHIBA, Otawara [132]	28	TE <sub>02</sub>	TE <sub>02</sub>	0.2	35.7	0.075
	41	TE <sub>02</sub>	TE <sub>02</sub>	0.2	31.3	0.1
	56	TE <sub>02</sub>	TE <sub>02</sub>	0.2	32.9	0.1
	70	TE <sub>02</sub>	TE <sub>02</sub>	0.025	28.4	0.001

SDC: Single-stage Depressed Collector

<sup>1)</sup> formerly VALVO, <sup>2)</sup> Communications & Power Industries, formerly VARIAN, <sup>3)</sup> 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]			
<b>CPI<sup>2)</sup>, Palo Alto</b> <b>[9,14,115,133-138]</b>	106.4(2 $\Omega_c$ )	TE <sub>02/03</sub>	TE <sub>03</sub>	0.135	21	0.1			
	106.4	TE <sub>12,2</sub>	TE <sub>12,2</sub>	0.4	30	0.1			
	110	TE <sub>15,2</sub>	TE <sub>15,2</sub>	0.5	28	1.0			
				0.3	28	2.0			
	110	TE <sub>22,2</sub>	TE <sub>22,2/4</sub>	0.5	27	2.5			
	110	TE <sub>22,6</sub>	TEM <sub>00</sub>	1.05	31	5.0			
				0.6	31	10.0			
			0.106	21	CW				
<b>FZK<sup>1)</sup>, Karlsruhe</b> <b>[38-40,139-148]</b>	117.9	TE <sub>19,5</sub>	TEM <sub>00</sub>	1.55	31	0.007			
				1.55	49.5 (SDC)	0.007			
	132.6	TE <sub>9,4</sub>	TE <sub>9,4</sub>	0.42	21	0.005			
<b>GYCOM-M (TORIY, IAP)</b> <b>Moscow, N. Novgorod</b> <b>[10,80,149-156]</b>	110	TE <sub>19,5</sub>	TEM <sub>00</sub>	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			
<b>GYCOM-N (SALUT, IAP)</b> <b>N. Novgorod</b> <b>[10,36,37,120-122,156-159]</b>	104	TE <sub>18,7</sub>	TEM <sub>00</sub>	0.9	44 (SDC)	0.05			
	106.4	TE <sub>15,4</sub>	TEM <sub>00</sub>	0.5	33	0.2			
	110	TE <sub>15,4</sub>	TEM <sub>00</sub>	0.5	33	1.0			
	111.5	TE <sub>19,6</sub>	TEM <sub>00</sub>	1.0	32	0.0001			
	129	TE <sub>17,7</sub>	TEM <sub>00</sub>	0.5	33	0.5			
<b>JAERI, TOSHIBA</b> <b>Naka, Otawara [160-169]</b>	110	TE <sub>22,2</sub>	TEM <sub>00</sub>	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			
				1.2	39 (SDC)	0.001			
	110	TE <sub>22,6</sub>	TEM <sub>00</sub>	1.0	39 (SDC)	3.0			
				0.32	36 (SDC)	5.0			
				110	TE <sub>22,12</sub>	TE <sub>22,12</sub>	0.7	30	0.001
				120	TE <sub>03</sub>	TE <sub>03</sub>	0.17	25	0.01
				120	TE <sub>12,2</sub>	TE <sub>12,2</sub>	0.46	24	0.1
							0.25	24	0.22
				120	TE <sub>12,2</sub>	TEM <sub>00</sub>	0.5	24	0.1
<b>MITSUBISHI, Amagasaki</b> <b>[170,171]</b>	120	TE <sub>02/03</sub>	TE <sub>03</sub>	0.16	25	0.06			
	120	TE <sub>15,2</sub>	TE <sub>15,2</sub>	1.02	32.5	0.0002			
				0.46	30	0.1			
			0.25	30	0.21				
<b>THALES ED<sup>3)</sup>, Velizy</b> <b>[83,131]</b>	100	TE <sub>34</sub>	TE <sub>34</sub>	0.19	30	0.07			
	110	TE <sub>93</sub>	TE <sub>93</sub>	0.42	17.5	0.002			
	110	TE <sub>64</sub>	TE <sub>64</sub>	0.34	19	0.01			
				0.39	19.5	0.21			
<b>THALES ED<sup>3)</sup>, CEA,CRPP,</b> <b>FZK [172-177]</b>	118	TE <sub>22,6</sub>	TEM <sub>00</sub>	0.7	37	0.01			
				0.53	32	5.0			
				0.35	23	111.0			

SDC: Single-stage Depressed Collector

<sup>1)</sup> formerly KfK, <sup>2)</sup> Communications & Power Industries, formerly VARIAN, <sup>3)</sup> 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]	
<b>CPI<sup>3)</sup>, Palo Alto</b> <b>[9,14,114,115]</b>	140	TE <sub>02,03</sub>	TE <sub>03</sub>	0.1	27	CW	
	140	TE <sub>15,2</sub>	TE <sub>15,2</sub>	1.04 0.32 0.2 (0.4)	38 31 31	0.0005 3.6 avg. (peak)	
<b>FZK<sup>1)</sup>, PHILIPS<sup>2)</sup> [83,139]</b> <b>FZK, Karlsruhe</b> <b>[38-42,83,139-148,</b> <b>178-192]</b>	140.8	TE <sub>03</sub>	TE <sub>03</sub>	0.12	26	0.4	
	140.2	TE <sub>10,4</sub>	TE <sub>10,4</sub>	0.69	28	0.005	
	140.2	TE <sub>10,4</sub>	TEM <sub>00</sub>	0.60 0.50 0.50	27 32 48(SDC)	0.012 0.03 0.03	
	140.5	TE <sub>10,4</sub>	TEM <sub>00</sub>	0.46	51(SDC)	0.2	
	140.1	TE <sub>22,6</sub>	TEM <sub>00</sub>	1.6 2.1	60(SDC) 53(SDC)	0.007 0.001	
	162.3	TE <sub>25,7</sub>	TEM <sub>00</sub>	1.48 1.48	35 50(SDC)	0.007 0.007	
	139.8	TE <sub>28,8</sub>	TEM <sub>00</sub>	1.0 0.64 0.47	50(SDC) 30(SDC) 23(SDC)	10 140 180	
<b>FZK<sup>1)</sup>, CRPP,</b> <b>THALES ED<sup>4)</sup>, CEA</b> <b>[193,194]</b> <b>GYCOM-M (TORIY, IAP)</b> <b>Moscow, N. Novgorod</b> <b>[10,121,151,152,153-156,</b> <b>195-205]</b>	140	TE <sub>22,6</sub>	TEM <sub>00</sub>	1.0 0.96 0.54 0.26 0.1	36 36 36 36 35	1.0 1.2 3.0 10.0 80.0	
		(dual-beam	output)	2x0.37 2x0.3 2x0.165	30 29 28	3.0 5.5 10.0	
	140	TE <sub>22,8</sub>	TEM <sub>00</sub>	1.7 1.2	42 68 (SDC)	0.0001 0.0001	
	139.85	TE <sub>22,8</sub>	TEM <sub>00</sub>	0.9	31	3.0	
	170	TE <sub>28,7</sub>	TEM <sub>00</sub>	1.0	32.5	0.0001	
	170	TE <sub>25,10</sub>	TEM <sub>00</sub>	1.4 1.0	35 62(SDC)	0.0001 0.0001	
	170.17	TE <sub>25,10</sub>	TEM <sub>00</sub>	1.0 0.8 0.5 0.27	45(SDC) 40(SDC) 40(SDC) 28	1.5 3.0 5.0 10.0	
	<b>GYCOM-N (SALUT, IAP)</b> <b>N. Novgorod</b> <b>[10,36,37,120-122,156,159,</b> <b>195]</b>	140	TE <sub>22,6</sub>	TEM <sub>00</sub>	0.8 0.88 0.55	32 50.5(SDC) 33	0.8 1.0 2.0
		140	TE <sub>22,10</sub>	TEM <sub>00</sub>	1.0	49 (SDC)	0.5
		158.5	TE <sub>24,7</sub>	TEM <sub>00</sub>	0.5	30	0.7
	<b>JAERI, TOSHIBA</b> <b>Naka, Otawara</b> <b>[165-168, 206-212]</b>	170	TE <sub>22,6</sub>	TEM <sub>00</sub>	0.45 0.25 0.25	19 19 32(SDC)	0.05 0.4 0.4
		170.1	TE <sub>31,8</sub>	TE <sub>31,8</sub>	1.15	29	0.0004
		170	TE <sub>31,8</sub>	TEM <sub>00</sub>	1.3 1.2 0.9	32 57(SDC) 43.4(SDC)	0.003 0.003 9.2
					0.45 0.3	32(SDC) 30(SDC)	47.0 60
				0.52 0.52	19 30(SDC)	1.0 1.0	
<b>NIFS, TOSHIBA</b> <b>Toki, Otawara</b> <b>[25,26,118,119,213]</b>		168	TE <sub>31,8</sub>	TEM <sub>00</sub>	0.52 0.52	19 30(SDC)	1.0 1.0

SDC: Single-stage Depressed Collector

<sup>1)</sup> formerly KfK, <sup>2)</sup> formerly VALVO, <sup>3)</sup> Communications & Power Industries, formerly VARIAN,<sup>4)</sup> formerly Thomson TETable 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	
<b>FZK<sup>1)</sup> Karlsruhe</b> <b>[188-192,214-231]</b> <b>Pulse length <math>\leq 17</math> ms</b>	137.78	TE <sub>27,16</sub>	TE <sub>27,16</sub>	1.03	24.3	yes	no	
	139.96	TE <sub>28,16</sub>	TE <sub>28,16</sub>	1.17	27.2	yes	no*	
			TEM <sub>00</sub>	0.95	20	yes	no	
				0.95	29(SDC)	yes	no	
				(dual beam output)				
	142.02	TE <sub>29,16</sub>	TE <sub>29,16</sub>	1.04	24.4	yes	no	
	138.70	TE <sub>27,14</sub>	TEM <sub>00</sub>	1.14	26.1	yes	no	
	146.70	TE <sub>28,15</sub>	TEM <sub>00</sub>	1.13	25.6	yes	no	
	156.90	TE <sub>30,16</sub>	TEM <sub>00</sub>	1.24	25.4	yes	no	
	164.98	TE <sub>31,17</sub>	TE <sub>31,17</sub>	1.17	26.7	yes	no	
			TEM <sub>00</sub>	2.2	28	yes	no	
				(single-beam output)				
				1.5	30	yes	no	
				1.5	48 (SDC)	yes	no	
	167.14	TE <sub>32,17</sub>	TEM <sub>00</sub>	1.22	25.6	yes	no	
<b>IAP, Nizhny Novgorod</b> <b>[8,10,121,232-238]</b> <b>Pulse length <math>\leq 0.1</math> ms</b>	45	TE <sub>15,1</sub>	TE <sub>15,1</sub>	1.25	43	no	no	
	100	TE <sub>21,18</sub>	TE <sub>21,18</sub>	1.0	35	yes	no	
				0.5	20	no	no	
	100	TE <sub>25,13</sub>	TE <sub>25,13</sub>	2.1	30	no	no	
	103	TE <sub>22,13</sub>	TE <sub>22,13</sub>	1.6	38	no	no	
				1.0	40	yes	yes	
				0.7	30	yes	no	
				0.3	14	no	no	
	110	TE <sub>17,7</sub>	TE <sub>17,7</sub>	0.7	25	no	no	
	110	TE <sub>20,13</sub>	TE <sub>20,13</sub>	1.15	35	yes	no	
	110	TE <sub>21,13</sub>	TE <sub>21,13</sub>	1.0	35	yes	no	
	140	TE <sub>28,16</sub>	TE <sub>28,16</sub>	1.5	33.5	yes	no*	
				1.15	50 (SDC)	yes	no	
1.17				35.2	yes	yes		
			TEM <sub>00</sub>	1.1	30	yes	no	
			(dual-beam output)					
224 (2 $\Omega_c$ )	TE <sub>33,8</sub>	TE <sub>33,8</sub>	0.1	11	yes	no		
<b>IAP, FZK<sup>1)</sup> Karlsruhe [214]</b> <b>Pulse length 30 <math>\mu</math>s</b>	133	TE <sub>27,15</sub>	TE <sub>27,15</sub>	1.3	29	no	no	
	140	TE <sub>28,16</sub>	TE <sub>28,16</sub>	1.0	23	no	no	
<b>MIT, Cambridge [239,240]</b> <b>Pulse length 3 <math>\mu</math>s</b>	137	TE <sub>25,11</sub>	TEM <sub>00</sub>	0.5	7.5	no	no	
	139.6	TE <sub>26,11</sub>	TEM <sub>00</sub>	0.9	13	no	no	
	142.2	TE <sub>27,11</sub>	TEM <sub>00</sub>	1.0	14.5	no	no	
	140	TE <sub>21,13</sub>	TEM <sub>00</sub>	0.5	7.5	no	no	

<sup>1)</sup> formerly KfK, \* very similar cavity and tube design

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

Institution	Frequency [GHz]	Mode cavity	Mode output	Power [MW]	Efficiency [%]	Pulse length [s]
<b>CPI<sup>1)</sup>, Palo Alto [114,115]</b>	8	TE <sub>21</sub>	TE <sub>10</sub>	0.4	26.6	0.0005
	(dual rectangular waveguide output)			0.4	34.2 (SDC)	0.0005
<b>CPI<sup>1)</sup>, NIFS Palo Alto, Toki [25,26,118]</b>	70.15	TE <sub>10,3</sub>	TEM <sub>00</sub>	0.6	47(SDC)	2.25
	84	TE <sub>15,3</sub>	TEM <sub>00</sub>	0.5	29	2.0
<b>FZK<sup>2)</sup>, Karlsruhe [38-41,139-148,180-192]</b>	117.9	TE <sub>19,5</sub>	TEM <sub>00</sub>	0.59	41 (SDC)	0.001
				0.25	32 (SDC)	0.2
<b>FZK<sup>1)</sup>, CRPP, THALES ED<sup>3)</sup>, CEA [193,194]</b>	140.2	TE <sub>10,4</sub>	TEM <sub>00</sub>	1.55	31	0.007
				1.55	49.5 (SDC)	0.007
<b>GYCOM-N (SALUT, IAP) Nizhny Novgorod [122,152,153,158,159]</b>	140.5	TE <sub>10,4</sub>	TEM <sub>00</sub>	0.50	32	0.03
				0.50	48 (SDC)	0.03
<b>GYCOM-N (SALUT, IAP) Nizhny Novgorod [122,152,153,158,159]</b>	140.1	TE <sub>22,6</sub>	TEM <sub>00</sub>	0.46	51 (SDC)	0.2
				1.6	60 (SDC)	0.007
<b>GYCOM-N (SALUT, IAP) Nizhny Novgorod [122,152,153,158,159]</b>	162.3	TE <sub>25,7</sub>	TEM <sub>00</sub>	2.1	53 (SDC)	0.001
				1.48	35	0.007
<b>GYCOM-N (SALUT, IAP) Nizhny Novgorod [122,152,153,158,159]</b>	139.8	TE <sub>28,8</sub>	TEM <sub>00</sub>	1.48	50 (SDC)	0.007
				1.0	50 (SDC)	10
<b>GYCOM-N (SALUT, IAP) Nizhny Novgorod [122,152,153,158,159]</b>	70	TE <sub>9,3</sub>	TEM <sub>00</sub>	0.64	30 (SDC)	140
				0.47	23 (SDC)	180
<b>GYCOM-N (SALUT, IAP) Nizhny Novgorod [122,152,153,158,159]</b>	82.7	TE <sub>10,4</sub>	TEM <sub>00</sub>	0.68	48 (SDC)	3.0
				0.65	38	3.0
<b>GYCOM-N (SALUT, IAP) Nizhny Novgorod [122,152,153,158,159]</b>	84	TE <sub>12,5</sub>	TEM <sub>00</sub>	0.65	53 (SDC)	0.03
				0.88	54 (SDC)	3.0
<b>GYCOM-N (SALUT, IAP) Nizhny Novgorod [122,152,153,158,159]</b>	104	TE <sub>18,7</sub>	TEM <sub>00</sub>	0.9	44 (SDC)	0.05
				1.2	40	0.0001
<b>GYCOM-N (SALUT, IAP) Nizhny Novgorod [122,152,153,158,159]</b>	110	TE <sub>19,5</sub>	TEM <sub>00</sub>	1.0	65 (SDC)	0.0001
				0.8	32	0.8
<b>GYCOM-N (SALUT, IAP) Nizhny Novgorod [122,152,153,158,159]</b>	140	TE <sub>22,6</sub>	TEM <sub>00</sub>	0.88	50.5 (SDC)	1.0
				1.0	49 (SDC)	0.5
<b>GYCOM-M (TORIY, IAP) Moscow, Nizhny Novgorod [43,204,205]</b>	140	TE <sub>22,10</sub>	TEM <sub>00</sub>	1.7	42	0.0001
				1.2	68 (SDC)	0.0001
<b>GYCOM-M (TORIY, IAP) Moscow, Nizhny Novgorod [43,204,205]</b>	170	TE <sub>25,10</sub>	TEM <sub>00</sub>	1.4	35	0.0001
				1.0	62 (SDC)	0.0001
<b>GYCOM-M (TORIY, IAP) Moscow, Nizhny Novgorod [43,204,205]</b>	170.17	TE <sub>25,10</sub>	TEM <sub>00</sub>	1.0	45 (SDC)	1.5
				0.8	40 (SDC)	3.0
<b>GYCOM-M (TORIY, IAP) Moscow, Nizhny Novgorod [43,204,205]</b>	115	QOG	TEM <sub>00</sub>	0.5	40 (SDC)	5.0
				0.60	9	10 <sup>-5</sup>
<b>GYCOM-M (TORIY, IAP) Moscow, Nizhny Novgorod [43,204,205]</b>	110	TE <sub>22,2</sub>	TEM <sub>00</sub>	0.43	12.7 (SDC)	10 <sup>-5</sup>
				0.20	16.1 (SDC)	10 <sup>-5</sup>
<b>JAERI, TOSHIBA Naka, Otawara [160-169,206-212]</b>	110	TE <sub>22,2</sub>	TEM <sub>00</sub>	0.61	30	0.05
				0.61	50 (SDC)	0.05
<b>JAERI, TOSHIBA Naka, Otawara [160-169,206-212]</b>	110	TE <sub>22,6</sub>	TEM <sub>00</sub>	0.35	48 (SDC)	5.0
				1.0	39 (SDC)	3.0
<b>JAERI, TOSHIBA Naka, Otawara [160-169,206-212]</b>	170	TE <sub>22,6</sub>	TEM <sub>00</sub>	0.32	36 (SDC)	5.0
				0.25	19	0.4
<b>JAERI, TOSHIBA Naka, Otawara [160-169,206-212]</b>	170.2	TE <sub>31,8</sub>	TEM <sub>00</sub>	0.25	32 (SDC)	0.4
				1.3	32	0.003
<b>JAERI, TOSHIBA Naka, Otawara [160-169,206-212]</b>	170.2	TE <sub>31,8</sub>	TEM <sub>00</sub>	1.2	57 (SDC)	0.003
				0.9	43.4 (SDC)	9.2
<b>JAERI, TOSHIBA Naka, Otawara [160-169,206-212]</b>	170.2	TE <sub>31,8</sub>	TEM <sub>00</sub>	0.75	40 (SDC)	17
				0.45	32 (SDC)	47.0
<b>JAERI, TOSHIBA Naka, Otawara [160-169,206-212]</b>	168	TE <sub>31,8</sub>	TEM <sub>00</sub>	0.3	30 (SDC)	60.0
				0.52	19	1.0
<b>NIFS, TOSHIBA Toki, Otawara [25,26,119,213]</b>				0.52	30 (SDC)	1.0

SDC: Single-stage Depressed Collector;

QOG: Quasi-Optical Gyrotron

<sup>1)</sup> Communications & Power Industries; formerly VARIAN, <sup>2)</sup> formerly KfK, <sup>3)</sup> 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]		
<b>FZK<sup>1)</sup>, Karlsruhe</b> <b>[38-42,146-148,189-192]</b>	114.2	TE <sub>18,5</sub>	TEM <sub>00</sub>	0.85	23	0.001		
	117.9	TE <sub>19,5</sub>	TEM <sub>00</sub>	1.0	27	0.001		
				1.55	49.5 (SDC)	0.007	optimized	
	121.6	TE <sub>20,5</sub>	TEM <sub>00</sub>	1.0	27	0.001		
	125.3	TE <sub>21,5</sub>	TEM <sub>00</sub>	1.0	27	0.001		
	128.9	TE <sub>22,5</sub>	TEM <sub>00</sub>	0.9	24.5	0.001		
	132.6	TE <sub>20,6</sub>	TEM <sub>00</sub>	0.85	23	0.001		
	136.2	TE <sub>21,6</sub>	TEM <sub>00</sub>	0.9	24.5	0.001		
	140.1	TE <sub>22,6</sub>	TEM <sub>00</sub>	1.0	27	0.001		
				1.6	60 (SDC)	0.007	optimized	
	143.7	TE <sub>23,6</sub>	TEM <sub>00</sub>	1.1	30	0.001		
	147.4	TE <sub>24,6</sub>	TEM <sub>00</sub>	1.1	30	0.001		
	151.2	TE <sub>25,6</sub>	TEM <sub>00</sub>	1.05	28.5	0.001		
	154.9	TE <sub>23,7</sub>	TEM <sub>00</sub>	0.95	26	0.001		
	158.5	TE <sub>24,7</sub>	TEM <sub>00</sub>	1.1	30	0.001		
	162.3	TE <sub>25,7</sub>	TEM <sub>00</sub>	1.0	27	0.001		
				1.48	50 (SDC)	0.007	optimized	
	166.0	TE <sub>26,7</sub>	TEM <sub>00</sub>	1.0	26	0.001		
	<b>GYCOM-N (SALUT, IAP)</b> <b>Nizhny Novgorod</b> <b>[36,37,43,159]</b>	121.5	TE <sub>20,5</sub>	TEM <sub>00</sub>	0.5	30	0.0001	
		140.0	TE <sub>22,6</sub>	TEM <sub>00</sub>	0.5	30	0.5	
158.5		TE <sub>24,7</sub>	TEM <sub>00</sub>	0.5	30	0.7		
105.1		TE <sub>17,6</sub>	TEM <sub>00</sub>	1.235	41.2	0.0001		
111.7		TE <sub>19,6</sub>	TEM <sub>00</sub>	1.373	42.9	0.0001		
124.3		TE <sub>20,7</sub>	TEM <sub>00</sub>	1.183	37.0	0.0001		
127.6		TE <sub>21,7</sub>	TEM <sub>00</sub>	1.331	41.6	0.0001		
140.1		TE <sub>22,8</sub>	TEM <sub>00</sub>	1.521	38.0	0.0001		
152.6		TE <sub>23,9</sub>	TEM <sub>00</sub>	1.414	44.2	0.0001		
156.0		TE <sub>24,9</sub>	TEM <sub>00</sub>	1.010	36.1	0.0001		
140.0		TE <sub>22,8</sub>	TEM <sub>00</sub>	1.7	42	0.0001		
				1.2	68 (SDC)	0.0001		
104		TE <sub>18,7</sub>	TEM <sub>00</sub>	0.9	45 (SDC)	0.05		
140		TE <sub>22,10</sub>	TEM <sub>00</sub>	1.0	51 (SDC)	0.5		

SDC: Single-stage Depressed Collector;

<sup>1)</sup> 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<sub>22,6</sub> 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 [42]. 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<sub>20,6</sub> to TE<sub>24,6</sub> in time steps of 1 s has been achieved.

Institution	Frequency [GHz]	Mode cavity	Mode output	Power [MW]	Efficiency [%]	Pulse length [s]
FZK <sup>1)</sup> , Karlsruhe [225-227,229,230]	136.3	TE <sub>26,14</sub>	TEM <sub>00</sub>	1.02	23.5	0.001
	138.7	TE <sub>27,14</sub>	TEM <sub>00</sub>	1.14	26.1	0.001
	140.8	TE <sub>28,14</sub>	TEM <sub>00</sub>	0.92	24.0	0.001
	142.2	TE <sub>26,15</sub>	TEM <sub>00</sub>	0.90	20.6	0.001
	144.4	TE <sub>27,15</sub>	TEM <sub>00</sub>	0.96	23.1	0.001
	146.7	TE <sub>28,15</sub>	TEM <sub>00</sub>	1.13	25.6	0.001
	149.0	TE <sub>29,15</sub>	TEM <sub>00</sub>	1.08	22.9	0.001
	151.1	TE <sub>30,15</sub>	TEM <sub>00</sub>	1.00	21.3	0.001
	152.4	TE <sub>28,16</sub>	TEM <sub>00</sub>	0.75	20.8	0.001
	154.6	TE <sub>29,16</sub>	TEM <sub>00</sub>	0.94	23.4	0.001
	156.9	TE <sub>30,16</sub>	TEM <sub>00</sub>	1.24	25.4	0.001
	159.2	TE <sub>31,16</sub>	TEM <sub>00</sub>	1.04	23.9	0.001
	160.7	TE <sub>29,17</sub>	TEM <sub>00</sub>	0.99	20.7	0.001
	162.8	TE <sub>30,17</sub>	TEM <sub>00</sub>	0.98	20.7	0.001
	165.1	TE <sub>31,17</sub>	TEM <sub>00</sub>	1.24	26.3	0.001
				1.24	41 (SDC)	0.001
	167.2	TE <sub>32,17</sub>	TEM <sub>00</sub>	1.22	25.6	0.001

SDC: Single-stage Depressed Collector;

<sup>1)</sup> 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 [237,238]. By biasing the inner rod of the FZK coaxial cavity gyrotron, such very fast (within  $\approx 0.1$  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<sub>31,17</sub> 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	10.0	GYCOM-M
		960	140	1.2	GYCOM-M
		550	140	3.0	GYCOM-M
		100	140	80.0	GYCOM-M
		1030	170	1.0	GYCOM-M
		500	170	5.0	GYCOM-M
		270	170	10.0	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 <sub>2</sub> edge cooled	530	118	5.0	CEA/CRPP/FZK/TED
		350	118	100.0	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
		500	170	0.6	JAERI/TOSHIBA
sapphire	distributed water cooled	65**	110	0.3	GA/JAERI
		200*	110	0.7	GA/CPI
Au-doped silicon	single-disk CO <sub>2</sub> gas edge cooled	600	140	0.8	GYCOM-M
diamond	single-disk water edge cooled	300**	110	1.0	CPI/FOM
		50	110	CW	CPI/FOM
		450	110	2.0	GYCOM-M/GA
		1050	110	5.0	CPI/GA
		550	110	10.0	CPI/GA
		1000	110	3.0	JAERI/TOSHIBA
		340	118	50.0	FZK/CEA/TED
		300	118	111.0	FZK/CEA/TED
		1000	140	10	FZK/CEA/CRPP/TED
		640	140	140	FZK/CEA/CRPP/TED
		470	140	180	FZK/CEA/CRPP/TED
		1000	170	1.5	GYCOM-M/FZK
		900	170	9.2	JAERI/TOSHIBA
		450	170	47.0	JAERI/TOSHIBA

Note: \* and \*\* indicates that the power corresponds to that of a 1 MW (\*) and 0.8 MW (\*\*) HE<sub>11</sub> mode, respectively.

Tab. IX: Experimental parameters of high-power millimeter-wave vacuum windows [10,14,27,30,83,115,119,138,149-156,165-169,172-177,193,194,202-205,210-213,242-274].

Material	BeO p.c.	BN (CVD) p.c.	Si <sub>3</sub> N <sub>4</sub> composite (SN-287)	Sapphire (Al <sub>2</sub> O <sub>3</sub> ) 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 $\sigma_B$ [MPa]	140	80	800	410	1000	500
Poissons Number $\nu$	0.3	0.25	0.28	0.22	0.1	0.1
Density $\rho$ [g/cm <sup>3</sup> ]	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. $\alpha$ [10 <sup>-6</sup> /K]	7.2	3	2.4	5.5	2.5	1.0
Permittivity (145 GHz) $\epsilon_r'$	6.7	4.7	7.84	9.4	11.7	5.67
Loss Tangent (145 GHz) $\tan\delta$ [10 <sup>-5</sup> ]	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 <sub>T</sub> $P_T = R'\rho c_p / ((1+\epsilon_r')\tan\delta)$	0.06	0.05	0.36	0.09	106	118
Radiation Sensitivity n(10 <sup>20</sup> -10 <sup>21</sup> n/m <sup>2</sup> ) $\gamma/X$ (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) [262].

Material	Sapphire (Al <sub>2</sub> O <sub>3</sub> ) s.c.	Silicon Au-doped s.c.	Diamond (PACVD) p.c.
Thermal Conductivity k [W/mK]	900 (20000)	1300	10000
Ultimate Bending Strength $\sigma_B$ [MPa]	410	1000	500
Poissons Number $\nu$	0.22	0.1	0.1
Density $\rho$ [g/cm <sup>3</sup> ]	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. $\alpha$ [10 <sup>-6</sup> /K]	5.5	2.5	1.2
Permittivity (145 GHz) $\epsilon_r'$	9.3	11.5	5.67
Loss Tangent (145 GHz) $\tan\delta$ [10 <sup>-5</sup> ]	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 <sub>T</sub> $P_T = R'\rho c_p / ((1+\epsilon_r')\tan\delta)$	71 (4460)	907	490
Radiation Sensitivity n(0.3 · 10 <sup>21</sup> n/m <sup>2</sup> ) $\gamma/X$ (0.75 Gy/s)	no no	no no	no no

Tab. XI: Thermophysical, mechanical and dielectrical parameters of window materials related to thermal load -failure resistance and power transmission capacity of edge-cooled windows at LN<sub>2</sub>-temperature - 77 K (LNe-Temperature - 30 K) (p.c.=poly-crystalline, s.c.=single-crystalline) [262].

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 [27-30,262]. 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, Si<sub>3</sub>N<sub>4</sub> 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 LN<sub>2</sub>-temperature 77 K (Lne-temperature 30 K) sapphire has a thermal conductivity of 900 (20000) W/mK and a loss tangent of  $5.7 \cdot 10^{-6}$  ( $2 \cdot 10^{-6}$ ) leading to  $R' = 130$  (2870) and  $P_T = 70$  (4460). The LN<sub>2</sub>-edge-cooled sapphire window of the 118 GHz TED gyrotron (0.5 MW, 210 s) [172-177] 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 [250].

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 [27-30,262]. 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 <sub>2</sub> 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 <sub>2</sub> 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 [27-30,262].

## 7 Very High Frequency Gyrotron Oscillators

Institution	Frequency [GHz]	Mode	Power [kW]	Efficiency [%]	Pulse length [ms]
<b>CPI<sup>1)</sup>, Palo Alto [275]</b>	250	TE <sub>11,1</sub> /TE <sub>11,2</sub>	10	3.4	0.1
<b>IAP, N. Novgorod [46,47,276]</b>	157	TE <sub>03</sub>	2.4	9.5	CW
	250	TE <sub>02</sub>	4.3	18	CW
	250	TE <sub>65</sub>	1	5	CW
	326	TE <sub>23</sub>	1.5	6.2	CW
<b>MIT, Cambridge [277,278]</b>	209	TE <sub>92</sub>	15	3.5	0.001
	241	TE <sub>11,2</sub>	25	6.5	0.001
	302	TE <sub>34</sub>	4	1.5	0.0015
	339	TE <sub>10,2</sub>	4	3	0.0015
	363	TE <sub>11,2</sub>	7	2.5	0.0015
	417	TE <sub>10,3</sub>	15	6	0.0015
	457	TE <sub>15,2</sub>	7	2	0.0015
	467	TE <sub>12,3</sub>	22	3.5	0.0015
	503	TE <sub>17,2</sub>	10	5.5	0.0015
<b>UNIVERSITY, Fukui [48-51,279-285]</b>	383	TE <sub>26</sub>	3	3.7	1
	402	TE <sub>55</sub>	2	3	1
	576	TE <sub>26</sub>	1	2.5	0.5

<sup>1)</sup> 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  $\geq 1$  kW.

Institution	Frequency [GHz]	Mode	Power [MW]	Efficiency [%]	Pulse length [ $\mu$ s]	
<b>IAP, Nizhny Novgorod [46,47]</b>	250	TE <sub>20,2</sub>	0.3	31	30 - 80	
	350		0.13	17	30 - 80	
	430		0.08	10	30 - 80	
	500	TE <sub>28,3</sub>	0.1	8.2	30 - 80	
	540		0.06	6	30 - 80	
	600	TE <sub>38,2</sub>	0.05	5	30 - 80	
	650		0.04	4	40	
<b>MIT, Cambridge [35,240,286-290]</b>	113.2	TE <sub>23,6</sub>	0.84	25	3	
	113.2	TE <sub>23,6</sub> /TEM <sub>00</sub>	0.84	17	3	
	140	TE <sub>04</sub>	0.025	7.4	3	PBG resonator BW = 35%
	140	TE <sub>15,2</sub>	1.33	40	3	
	148	TE <sub>16,2</sub>	1.3	39	3	
	166.6	TE <sub>27,8</sub>	1.50	34	3	
	170.0	TE <sub>28,8</sub>	1.50	35	3	
	173.4	TE <sub>29,8</sub>	0.72	29	3	
	188	TE <sub>18,3</sub>	0.6		3	
	225	TE <sub>23,3</sub>	0.37		3	
	231	TE <sub>38,5</sub>	1.2	20	3	
	236	TE <sub>21,4</sub>	0.4		3	
	267	TE <sub>28,4</sub>	0.2		3	
	280	TE <sub>25,13</sub>	0.78	17	3	
	287	TE <sub>22,5</sub>	0.537	19	3	
	320	TE <sub>29,5</sub>	0.4	20	3	
	327	TE <sub>27,6</sub>	0.375	13	3	
<b>UNIVERSITY, Fukui [280,285]</b>	278	TE <sub>33</sub>	0.001	5	1000	
	290	TE <sub>62</sub>	0.001	4	1000	
	314	TE <sub>43</sub>	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<sub>8,6</sub> mode, 2nd harmonic) [48-51,279-285,291,292].

Institution	Frequency [GHz]	Mode	Voltage [kV]	Current [A]	Power [MW]	Efficiency [%]	
MIT, Cambridge [287]	187.7	TE <sub>32,4</sub>	94	57	0.65	12	
	201.6	TE <sub>35,4</sub>	97	54	0.92	18	
	209.5	TE <sub>33,5</sub>	98	37	0.54	15	
	213.9	TE <sub>34,5</sub>	95	51	0.89	18	
	218.4	TE <sub>35,5</sub>	90	44	0.56	14	
	224.3	TE <sub>33,6</sub>	91	60	0.90	17	
	228.8	TE <sub>34,6</sub>	92	59	0.97	18	
				100	59	1.2	20
	265.7	TE <sub>39,7</sub>	90	57	0.64	12	
	283.7	TE <sub>43,7</sub>	92	35	0.33	10	
	291.6	TE <sub>41,8</sub>	93	54	0.887	18	

Table XV: Step tuning of MIT gyrotron oscillator (with large MIG [287]) operating at the fundamental electron cyclotron resonance frequency (pulse length 1.5  $\mu$ s).

Institution	Frequency [GHz]	Mode	Voltage [kV]	Current [A]	Power [MW]	Efficiency [%]
MIT, Cambridge [287]	249.6	TE <sub>24,11</sub>	71	41	0.39	14
	257.5	TE <sub>23,12</sub>	87	41	0.33	9
	267.5	TE <sub>25,12</sub>	85	33	0.35	12
	277.2	TE <sub>27,12</sub>	78	42	0.45	14
	280.1	TE <sub>25,13</sub>	92	51	0.78	17
	285.2	TE <sub>26,13</sub>	93	41	0.42	11
	282.8	TE <sub>23,14</sub>	94	39	0.54	15
	287.9	TE <sub>24,14</sub>	94	51	0.64	14
	292.9	TE <sub>25,14</sub>	95	41	0.72	18
	302.7	TE <sub>27,14</sub>	96	43	0.27	7

Table XVI: Step tuning of MIT gyrotron oscillator (with small MIG [287]) operating at the fundamental electron cyclotron resonance frequency (pulse length 1.5  $\mu$ s).



## 8 Gyrotrons for Technological Applications

Institution	Frequency [GHz]	Mode cavity	Mode output	Power [kW]	Efficiency [%]	Voltage [kV]	Magnet
<b>CPI<sup>1)</sup>, Palo Alto [9,14,275]</b>	28	TE <sub>02</sub>	TE <sub>02</sub>	15	38	40	roomtemp.
	28 (2Ω <sub>c</sub> )	TE <sub>02</sub>	TE <sub>02</sub>	10.8	33.6	30	roomtemp.
	60	TE <sub>02</sub>	TE <sub>02</sub>	30	38	40	cryo. mag.
<b>CPI, NIFS [25,116-119] Palo Alto, Toki</b>	84	TE <sub>15,3</sub>	TEM <sub>00</sub>	50	14	80	cryo. mag.
<b>GYCOM/IAP Nizhny Novgorod, [1,10,37,52-54,57-60 121,195,196,293-300]</b>	15	TE <sub>01</sub>	TE <sub>01</sub>	4	50	15	roomtemp.
	24.1 (2Ω <sub>c</sub> )	TE <sub>11</sub>	TE <sub>11</sub>	3.5	23	12	roomtemp.
	24.15	TE <sub>32</sub>	TE <sub>32</sub>	36	50	33	roomtemp.
	23 (2Ω <sub>c</sub> )	TE <sub>12</sub>	TE <sub>12</sub>	13	50	25	roomtemp.
				28	32	25	roomtemp.
	30 (2Ω <sub>c</sub> )	TE <sub>02</sub>	TE <sub>02</sub>	10	42	26	roomtemp.
				30	35	26	roomtemp.
	28.25 (2Ω <sub>c</sub> )	TE <sub>12</sub>	TE <sub>12</sub>	12	24	25	PM, 68 kg
	31.8-34.8	TE <sub>11</sub>	TE <sub>11</sub>	1.2	40	12	mech. tun.
	35.5-37.5	TE <sub>01</sub>	TE <sub>01</sub>	0.5	15.3	16	mech. tun.
	35.15	TE <sub>02</sub>	TE <sub>02</sub>	9.7	43	25	cryo. mag.
	35	TE <sub>02</sub>	TEM <sub>00</sub>	10-40	30-40	25-30	cryo. mag.
	37.5	TE <sub>62</sub>	TEM <sub>00</sub>	20	35	30	cryo. mag.
	68-72	TE <sub>13</sub>	TE <sub>13</sub>	1.4	22	17.5	mech. tun.
	83	TE <sub>93</sub>	TEM <sub>00</sub>	10-40	30-40	25-30	cryo. mag.
	150	TE <sub>03</sub>	TE <sub>03</sub>	22	30	40	cryo. mag.
160 (2Ω <sub>c</sub> )	TE <sub>03</sub>	TE <sub>03</sub>	2.4	9.5	18	cryo. mag.	
191.5 (2Ω <sub>c</sub> )			0.55	6.2	22	cryo. mag.	
250 (2Ω <sub>c</sub> )			1	5	20	cryo. mag.	
326 (2Ω <sub>c</sub> )			1.5	6	20	cryo. mag.	
<b>MITSUBISHI, Amagasaki [56,301-303]</b>	28 (2Ω <sub>c</sub> )	TE <sub>02</sub>	TE <sub>02</sub>	10	38.7	21	PM, 600 kg tapered B

<sup>1)</sup> Communications & Power Industries, formerly VARIAN

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
<b>IAP, Nizhny Novgorod [304-306]</b>	9.23	TE <sub>01</sub>	0.28	0.06	10 (7.7)	30 (46)	slotted echelette cavity, n = 3-10
	20	TM <sub>01</sub>	0.5	0.7	40	11.4	
	79-107	TM <sub>1n</sub>	0.5	2-6.5	30	3-1	
<b>IAP, Nizhny Novgorod Lebedev/General Phys. Inst. Moscow [305,307-309]</b>	10	TE <sub>13</sub>	0.3	0.4	25	20	slotted cavity
	10	TE <sub>13</sub>	0.3	1.0	60	15	plasma-filled slotted cavity
	40	TE <sub>13</sub>	0.4	1.3	25	5	slotted cavity
<b>UNIV. Michigan [310-316]</b>	2.88	TE <sub>01</sub> <sup>r</sup>	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 <sub>10</sub> <sup>r</sup>	0.8	0.35 (1.2)	14	5.0 (0.15)	large orbit
			2.5	TE <sub>11</sub> <sup>c</sup> (coax.)	0.8	0.8 (4.0)	90
	10	TE <sub>11</sub>	40				unslotted cavity
			20				unsl. noncoax. cavity
10	TE <sub>11</sub>	0.4	0.025	0.6	6		
<b>NRL, Washington D.C. [317-320]</b>	8.35-13	4-5 modes	3.3	80	1000	0.4	superradiant
	35	TE <sub>62</sub>	0.78	1.6 (3.5)	100	8 (4) <sup>*</sup>	slotted cavity
			1.15	2.5	275	10	
35	TE <sub>13</sub>	0.9	0.65	35	6		
<b>Tomsk Polytech. Inst. [321]</b>	3.1		0.75	8.0 (30)	1800	8	also vircator interaction
<b>UNIV. Strathclyde [322-325]</b>	23	TE <sub>12</sub>	0.1	0.5	5	10%	
	100		0.2	0.22	6.3	14	

r: rectangular waveguide

<sup>\*</sup>) operation from 28 to 49 GHz by magnetically tuning through a family of TE<sub>m2</sub> 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 [%]
<b>IAP, Nizhny Novgorod [326-329]</b>	21.6	TE <sub>11</sub>	1	0.3	0.03 (3)	1.5	16.7 (0.17)
	35.7	TE <sub>21</sub>	2	0.3	0.03 (3)	1.5	16.7 (0.17)
	49.1	TE <sub>31</sub>	3	0.3	0.03 (3)	0.6	6.7 (0.07)
	62.4	TE <sub>41</sub>	4	0.3	0.03 (3)	0.2	2.2 (0.02)
	74.9	TE <sub>51</sub>	5	0.3	0.03 (3)	0.12	1.3 (0.013)
	130.3	TE <sub>42</sub>	4	0.25	0.01	0.1	4.0

Table XIX: Relativistic large orbit harmonic pulse gyrotrons with axis-encircling electron beam ( $\tau = 10$  ns). The 130 GHz experiment employed a thermionic gun.

## 10 Quasi-Optical Gyrotrons

Institution	Frequency [GHz]	Mode resonator	Power [kW]	Efficiency [%]	Pulse length [ms]	Type
ABB, Baden [83,112]	92	TEM <sub>00q</sub>	90	10	10	
CRPP, Lausanne [33,34,83,330]	90.8	TEM <sub>00q</sub>	150	15	5	
	100	TEM <sub>00q</sub>	90	15	15	
	200 (2Ω <sub>c</sub> )	TEM <sub>00q</sub>	8	3.5	15	
IAP, Nizhny Novgorod [331]	100	TE <sub>061</sub>	260	6.5	0.04	echelette cavity
MIT, Cambridge [332,333]	136	HE <sub>061</sub> <sup>0</sup>	83	18	0.003	confocal
	114.3	HE <sub>051</sub> <sup>0</sup>	75	16	0.003	slot-cavity
Moscow-State UNIV. [334]	35	TEM <sub>00q</sub>	1	15	CW	
	95	TEM <sub>00q</sub>	1	15	CW	
NRL, Washington D.C. [241,335,336]	110	TEM <sub>00q</sub>	80	8	0.013	
	115	TEM <sub>00q</sub>	431	12.7 (SDC)	0.013	
			197	16.1 (SDC)	0.013	
	120	TEM <sub>00q</sub>	600	9	0.013	
			200	12	0.013	
TOSHIBA, Otawara [132]	112	TEM <sub>00q</sub>	100	12	5	
	120	TEM <sub>00q</sub>	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 <sub>11</sub> <sup>*</sup> /TE <sub>21</sub> (2Ω <sub>c</sub> )	3.4	17 (0.21)	-	1.05-1.2	0.40	0.05 (4)	CARM-BWO
IAP	35.7	TE <sub>51</sub>	30	10	-	1.12	0.4	0.6	oscillator
IAP	36.5	TE <sub>11</sub>	9	18 (0.45)	-	1.15	0.4	0.6	oscillator
IAP, IHCE	37.5	TE <sub>11</sub>	10	4	30	0.5	0.5	0.5	amplifier
IAP, U. Strath., HERC	37.5	TE <sub>21</sub>	0.2	0.5 (0.25)			0.15	0.25 (0.5)	superradiance
IAP	38	TE <sub>11</sub> <sup>*</sup> /TE <sub>21</sub> (2Ω <sub>c</sub> )	13	26 (0.65)	-	1.24	0.5	0.1 (4)	CARM-gyrotron
	40	TE <sub>11</sub>	6	22 (0.44)	-		0.46	0.06 (0.3)	oscillator
IAP, IHCE, JINR	50	TE <sub>11</sub>	30	10	-	0.7	1.0	0.3	oscillator
IAP	66.7	TE <sub>21</sub>	15	3	-	0.6	0.5	1.0	oscillator
IAP, IHCE, JINR	68	TE <sub>11</sub>	50	8	-	1.0	1.2	0.5	oscillator
IAP	69.8	TE <sub>11</sub>	6	4	-	0.6	0.35	0.4	oscillator
IAP [326,327,337-346]	125	TE <sub>41</sub>	10	2	-	0.9	0.5	1.0	oscillator
LLNL Livermore [347]	220	TE <sub>11</sub>	50	2.5	-	3.0	2.0	1.0	oscillator
MIT Cambridge [85,348,349]	27.8	TE <sub>11</sub>	1.9	5.3	-	0.6	0.45	0.080	oscillator
	30	TE <sub>11</sub>	0.1	3	-	0.64	0.3	0.012	oscillator
	32	TE <sub>11</sub>	0.11	2.3	-	0.63	0.32	0.015	oscillator
	35	TE <sub>11</sub>	12	6.3 (0.04)	30	0.7	1.5	0.13 (20)	amplifier
UNIV. Michigan [350,351]	15	TE <sub>11</sub>	7	1.5	-	0.45	0.4	1.2	oscillator
UNIV. Strathclyde [352-354]	13	TE <sub>11</sub>			-	0.3	0.4	0.04	oscillator
	14.3 (2Ω <sub>c</sub> )	TE <sub>21</sub>	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 [86]	9.5	TM <sub>01</sub>	35	3.5	-	1.15	0.4	2.5	oscillator corr.w.g.
Tomsk Polytechn. Inst. [87]	25		20	0.2	-	0.64	0.9	14	oscillator diel.w.g.
UNIV. Niigata, NIFS, UNIV. Maryland [88]	19.5	TM <sub>01</sub>	0.2	3.8	-	0.9	0.035	0.15	oscillator corr.w.g.
UNIV. Yale, NRL, Washington D.C. [89]	6.2	TE <sub>01</sub>	0.02	10	53	0.2	0.05	0.005	amplifier diel.w.g.

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

## 12 Gyroklystrons, Gyro-TWT's, Gyrotwystrons, Gyro-BWOs and other Gyro-Devices

- Weakly Relativistic Pulse Gyroklystrons

Institution	Frequency [GHz]	Mode	No. of cavities	Power [kW]	Efficiency [%]	Gain [dB]	BW [%]	Type
CPI <sup>1)</sup> , Palo Alto [14,81]	10 ( $2\Omega_c$ )	TE <sub>01</sub>	3	20	8.2	10	0.2	
	28	TE <sub>01/02</sub>	2	76	9	30	0.2	
	35		2	65		30	0.2	
CPI, Litton, NRL, U.M. [355-360]	93.8	TE <sub>01</sub>	4	118	29.5	24.7	0.64	SN1
			5	130	33	39.5	0.75	SN2
GYCOM-M(TORIY), Moscow [361,362]	35.2	TE <sub>02</sub>	2	750 (5av.)	24	20	0.6	max. power
			2	350	32	19	0.9	max. efficiency
	35.0	TE <sub>01</sub>	4	160	48	42	1.4	
	3		250 (1.2av.)	35	40	1.4		
IAP Nizhny Novgorod [361,362-374]	9.25	TE <sub>01</sub>	2	4	50	22	1.0	
			3	16	45	22	1.0	
	15.2	TE <sub>01</sub>	3	50	50	30	0.5	
		TE <sub>02</sub>	3	160	40	30	0.5	max. efficiency
	15.8	TE <sub>01</sub>	4	280	32	34	0.53	
		TE <sub>02</sub>	2	258	18	17	0.3	tapered B-field
	35.12 ( $2\Omega_c$ )	TE <sub>02</sub>	2	300	22		0.3	2-cav. gyrotron
				230	30		0.3	2-cav. gyrotron
	93.2	TE <sub>01</sub>	4	65	26	35	0.3	max. power
				57	34	40	0.3	max. efficiency
	93.5	TE <sub>02</sub>	2	140	18	18	0.35	
				207	30	21	0.2	shaped B
	93.2	TE <sub>02</sub>	3	340	24.5	23	0.3	shaped B
NRL, Washington D.C. [67,81,241,375-386]	4.5	TE <sub>10</sub>	3	54	30	30	0.4	
	34.95	TE <sub>01</sub>	2	210	37	24	0.35	
	34.9	TE <sub>01</sub>	3	225	31	30	0.82	
	34.9	TE <sub>01</sub>	4	208	30	53	0.5	
	85	TE <sub>13</sub>	2	50		20		
	85.5	TEM <sub>00</sub>	2	82	19	18		QOGK
				82	30 (SDC)	18		QOGK
	93.4	TE <sub>01</sub>	4	60	25	27	0.69	max. BW
84				34	42	0.37	max. power	
72				27	48	0.44	max. pow.xBW	

- Weakly Relativistic CW Gyroklystrons

Institution	Frequency [GHz]	Mode	No. of cavities	Power [kW]	Efficiency [%]	Gain [dB]	BW [%]	Type
CPI, Litton, NRL, U.M. [67,355-360]	93.8	TE <sub>01</sub>	4	10.1	33.5	32	0.45	(92 kW, 11% duty)
	94.2	TE <sub>01</sub>	5	10.2	31	33	0.75	(102 kW, 10% duty)
IAP Nizhny Novgorod [365]	9.17	TE <sub>11</sub>	2	0.7	70	22	0.3	
IAP/ISTOK Moscow [366,369]	91.6	TE <sub>01</sub>	4	2.5	25	31	0.36	

QOGK: Quasi-optical Gyroklystron;

SDC: Single-stage Depressed Collector

<sup>1)</sup> Communications & Power Industries, formerly VARIAN

Table XXIII: Weakly relativistic gyroklystron experimental results.

Institution	Frequency [GHz]	Mode	No. of cavities	Power [MW]	Efficiency [%]	Gain [dB]	BW [%]	Type
UNIV. Maryland [61-63,387-395]	8.57	TE <sub>01</sub>	3	80	32	30	0.2	coaxial
	9.875	TE <sub>01</sub>	2	24	30	33	0.2	
	9.87	TE <sub>01</sub>	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	28	13	25	0.1	coaxial
	17.14 (2Ω <sub>c</sub> )	TE <sub>02</sub>	3	28	13	25	0.1	
	19.75 (2Ω <sub>c</sub> )	TE <sub>02</sub>	2	32	29	27	0.1	
29.57 (3Ω <sub>c</sub> )	TE <sub>03</sub>	2	1.8	2.0	14	0.1		

Table XXIV: Relativistic pulse gyrokystron experimental results.

Institution	Frequency [GHz]	Mode	Power [kW]	Efficiency [%]	Gain [dB]	Bandwidth [%]	Type
CPI <sup>1)</sup> , Palo Alto [15,81,396,397]	5.18	TE <sub>11</sub>	120	26	20	7.3	MIG
	5.2	TE <sub>11</sub>	64	14	17.5	7.3	Pierce-helix gun
	35	TE <sub>11</sub>	50				Pierce-helix gun
	93.7	TE <sub>11</sub>	28	7.8	31	2	Pierce-helix gun
IAP, Nizhny Novgorod [398,399]	36.4	TE <sub>-21</sub> /TE <sub>+11</sub>	72	15	9	4	quasi-Pierce gun with kicker
NRL, Washington D.C. [81,400-402]	32.5	TE <sub>10</sub>	6.3	10	16.7	33	1-stage tapered
	35.5	TE <sub>10</sub>	8	16	25	20	2-stage tapered
	32.3	TE <sub>10</sub>	50	28	25	11	folded waveguide axis-encircl. beam
	34.3	TE <sub>01</sub>	16.6	7.8	20	1.4	
UCLA Los Angeles [403-411]	9.3	TE <sub>10</sub>	55	11	27	11	diel. coat. waveg. axis-encircl. beam
	10.4 (3Ω <sub>c</sub> )	TE <sub>31</sub>	6	5	11	3	
	15.7 (2Ω <sub>c</sub> )	TE <sub>21</sub>	207	12.9	16	2.1	slotted waveg.
	16.2 (8Ω <sub>c</sub> )	TE <sub>82</sub>	0.5	1.3	10	4.3	axis-encircl. beam
UNIV. Hsinchu [91,372-377,412-416]	35.8	TE <sub>11</sub>	18.4	18.6	18	10	
	35.8	TE <sub>11</sub>	27	16	35	7	2-stage severed
	34.2	TE <sub>11</sub>	62	21	33	12	2-stage lossy (short)
	33.6	TE <sub>11</sub>	93	26.5	70	8.6	2-stage lossy (long)

1) Communications &amp; 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 [92,399,417-421]	9.4 ( $2\Omega_c$ )	TE <sub>21</sub> /TE <sub>+11</sub>	1.1	29	37	21	helical waveguide with $\Delta m=3$ perturb. axis encircl. e-beam
	36.5 ( $2\Omega_c$ )	TE <sub>21</sub> /TE <sub>+11</sub>	3.0	27	33	20( $\Delta B$ )	see above
MIT, Cambridge [422]	17.1 ( $2\Omega_c$ )	TE <sub>21</sub>	2	4	40		Pierce-helix gun
	17.1 ( $3\Omega_c$ )	TE <sub>31</sub>	4	6.6	51		Pierce-helix gun
NRL, Washington D.C. *) [423,424]	35	TE <sub>11</sub>	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	Mode output w.g.	Power [kW]	Efficiency [%]	Gain [dB]	BW [%]
NRL, Washington D.C. [425]	4.5	TE <sub>10</sub>	TE <sub>10</sub>	73	22.5	37	1.5
	31.5	TE <sub>42</sub> ( $2\Omega_c$ )	TE <sub>42</sub>	160	25	30	1.3
	93.5	TE <sub>01</sub> (3 cav.)	TE <sub>01</sub>	50	17.5	30	1.0
IAP, N.Novgorod, NRL Washington D.C. [426,427]	9.2	TE <sub>01</sub> (2 cav.)	TE <sub>01</sub>	4.8	14	20	0.9
				4.4	27.5	18	1.6

- Weakly Relativistic Pulse Harmonic-Multiplying Inverted Gyrotwystrons

Institution	Frequency [GHz]	Mode cavity	Mode output w.g.	Power [kW]	Efficiency [%]	Gain [dB]	BW [%]
NRL, Washington D.C. [93,428-431]	31.8	TE <sub>22</sub>	TE <sub>42</sub> ( $2\Omega_c$ )	100	20	30	1.3
	33.7	TE <sub>02</sub>	TE <sub>03</sub> ( $2\Omega_c$ )	430	35	30	0.3
	34.6	TE <sub>02</sub>	TE <sub>03</sub> ( $2\Omega_c$ )	180	32	30	3.0
	32.5	TE <sub>02</sub>	TE <sub>03</sub> ( $2\Omega_c$ )	200	12	36	3.0
						phase-locked oscillator gyro-TWT	

- Relativistic Pulse Gyrotwystrons

Institution	Frequency [GHz]	Mode cavity	Mode output w.g.	Power [MW]	Efficiency [%]	Gain [dB]	BW [%]
UNIV. Maryland [432]	9.878	TE <sub>01</sub>	TE <sub>01</sub>	21.6	21	25.5	
	19.76	TE <sub>01</sub> (9.88GHz)	TE <sub>02</sub> ( $2\Omega_c$ )	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, Nizhny Novgorod [399]	35-38	TE <sub>-21</sub> /TE <sub>11</sub>	34	7	15	quasi-Pierce gun with kicker
MIT, Cambridge, LLNL, Livermore [433]	140	TE <sub>12</sub> <sup>c</sup>	2	2	9	
NRL, Washington D.C. [434]	27.8	TE <sub>10</sub> <sup>r</sup>	2	9	3	electr. tuning
UNIV. Hsinchu [435-437]	29.2	TE <sub>10</sub> <sup>r</sup>	6	15	13	magn. tuning
	33.5	TE <sub>11</sub> <sup>c</sup>	20-67	6.5-21.7	5	injection locked
			100	25		free running
			154	39	1	injection locked
UNIV. Utah [438]	10	TE <sub>10</sub> <sup>r</sup>	164	41	1	inverse injec. locked
			0.72	10	8	

r = rectangular waveguide; c = circular waveguide

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

Institution	Frequency [GHz]	Mode	Power [MW]	Efficiency [%]	BW [%]	Voltage [MV]	Current [kA]	Type
IAP, N. Novgorod [439,440]	10	TM <sub>11</sub>	200	22		0.45	2	Cherenkov with cycl. mode selection
	35(2Ωc)	TE <sub>-21</sub> / TE <sub>+11</sub>	1.15	10	15(ΔB) axis encirl.	0.35	0.032	hel. w.g. with Δm=3 perturb.
UNIV. Kanazawa [441,442]	9-13	TE <sub>10</sub> <sup>r</sup>	1	0.75 (0.02)	1	0.45	0.3(10)	
UNIV. Michigan [443,444]	4-6	TE <sub>11</sub>	55(30)	8(4.3)	1	0.7	1	
	5-6(2Ωc)	TE <sub>11</sub>	1	0.15	4			
USAF Phillips Lab. Aberdeen [445,446]	4.2	TE <sub>21</sub>	4	1	1	0.4	1	
	4.4	TE <sub>01</sub>	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 [447-455]	10.0	TE <sub>11</sub> <sup>r</sup>	TE <sub>11</sub> <sup>r</sup>	10	36	0.02	magnetron-type cavity
	10.5 (2Ω <sub>c</sub> )	TE <sub>31</sub> <sup>c</sup>	TE <sub>31</sub> <sup>c</sup>	0.7	10		
				1.3	7		
	30.3 (3Ω <sub>c</sub> )	TE <sub>41</sub> <sup>c</sup>	TE <sub>01</sub> <sup>c</sup>	6.9	35 (75 electr.)		
				6.9	44(SDC) (92 electr.)		
	100 (10Ω <sub>c</sub> )	TE <sub>11,1</sub> <sup>c</sup>	TE <sub>01</sub> <sup>c</sup>	0.32	1.7 (5 electr.)		
	10	TE <sub>21</sub> <sup>c</sup>	TE <sub>21</sub> <sup>c</sup>	1.5	25		auto-res.

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

Table XXIX: Experimental results of peniotrons.

Institution	Frequency [GHz]	Mode	Power [kW]	Efficiency [%]	Pulse length [ms]
UNIV. Tohoku, Sendai	69.85 (3Ω <sub>c</sub> )	TE <sub>02</sub>	8	6.75	0.2
Toshiba, Otawara	140 (3Ω <sub>c</sub> )	TE <sub>03</sub>	8	1	1
UNIV. Fukui [456]					

Table XXX: Experimental results of gyropeniotrons.

Institution	Frequency [GHz]	No. of Cavities	Voltage [MW]	Current [A]	Power [MW]	Efficiency [%]	Gain [dB]	Pulse [μs]
BINP, Novosibirsk [95,457-460]	0.915	3	0.3	12	2.6	73	30	30
	7.01 (2Ω <sub>c</sub> )	5	0.427	230	55	56	72	1.1
NRL, Washington D.C. [461]	11.16 (2Ω <sub>c</sub> )	6	0.65	225	14	10	unstable	0.1

BINP: Budker Institute of Nuclear Physics

Table XXXI: Experimental results of magnetrons.

### 13 Free Electron Masers (FEMs)

Institution	Frequency [GHz]	$B_w$ [T]	$\lambda_w$ [mm]	Mode	Power [MW]	Efficiency [%]	Gain [dB]	Voltage [MV]	Current [kA]	Accelerator	Pulse-Length [ $\mu$ s]	Type
CEA/CESTA, LeBarp [462-471]	3	0.11	120	TE <sub>11</sub> <sup>c</sup>	40	2.3		2.2	0.8	Ind. LINAC	0.025	spont.emiss.
	33-36	0.3	80	TE <sub>11</sub> <sup>c</sup>	50	7.1(0.06)	43	1.75	0.4(50)	Pulse Line	0.01	amplifier
	35	0.11	120	TE <sub>11</sub> <sup>c</sup>	80	4.5(3.7)	39	2.2	0.8(1.0)	Ind. LINAC	0.01(0.05)	amplifier
	35	0.17	200	TE <sub>11</sub> <sup>c</sup>	150	2.8(0.75)	45	6.7	0.8(3.0)	Ind. LINAC	0.01	amplifier
Columbia U. NY [472-474]	24	0.05/0.04	34/23	TE <sub>11</sub> <sup>c</sup> /TM <sub>11</sub> <sup>c</sup>	1	3.3	20	0.58	0.1	Pulse Line	0.15	amplifier
	150	0.18	17	TE <sub>11</sub> <sup>c</sup>	5	5		0.8	0.12	Pulse Line	0.15	oscillator
	100	0.1	20	TE <sub>02</sub> <sup>c</sup>	1	2		0.5	0.15	Pulse Line	0.03	spont.emiss.
DLR, Stuttgart [475]	85-150	0.61	25	TE <sub>01</sub> <sup>r</sup>	0.0015	0.19		2.3	0.00035	Microtron	5.5	oscillator
ENEA Frascati [476-478]	120	0.03	20	TE <sub>11</sub> <sup>c</sup>	11.5	6.4		0.6	0.3	Electrostatic	0.02	superrad.
EP Palaiseau [479]	206	0.2/0.16	40	HE <sub>10</sub> <sup>r</sup>	0.73(0.5)	5.7(3.9)		1.77	0.0072	Electrostatic	0.5(3.5)	oscillator
FOM Nieuwegein [100-108,480]	167	0.16	40	HE <sub>10</sub> <sup>r</sup>	0.36(0.26)	3.1(2.3)		1.61	0.0071	Electrostatic	0.5(3.0)	oscillator
General Electric Microwave Lab. Palo Alto [98]	169	0.16	40	HE <sub>10</sub> <sup>r</sup>	0.1	0.9 (14 with MDC)		1.60	0.007	Electrostatic	36	oscillator
	2.6	0.04	74.2	TE <sub>01</sub> <sup>r</sup>	1.2	10	6	0.17	0.07	Modulator	5.0	amplifier
	2.6-3.7	0.04	74.2	TE <sub>01</sub> <sup>r</sup>	0.9	9.2	10	0.135	0.07	Modulator	5.0	amplifier
	15.7	0.2	23.6	TE <sub>01</sub> <sup>c</sup>	1.65	6	6	0.23	0.125	Modulator	5.0	amplifier
IEE, China [109]	54	0.2	3.18	TE <sub>01</sub> <sup>c</sup>	0.15	6	10(30)	0.07	0.037	Modulator	4.0	amplifier
	35	0.31	110		140	5.2	57	3.4	0.95	Ind. LINAC	0.05	amplifier
	16.7	0.02		TE <sub>01</sub> <sup>c</sup>	300	11		0.6	4.5	Electrostatic	0.03	oscillator
IAP, Nizhny Novgorod [481-483]	42.8-47.2	0.03	24	TE <sub>10</sub> <sup>r</sup>	7	12(0.5)		0.5	0.12(3)	Pulse Line	0.015	oscil./CRM
IAP/INP Novosib. [484-489]	75	0.10	40	TEM	100	4.2		0.8	3.0	Pulse Line	1.0	oscillator
IAP/U. Strath./HERC [490-492]	28	0.22	16	TE <sub>11</sub> <sup>c</sup>	0.15	0.38		0.2	0.2	Pulse Line	0.0005	superrad.
JINR Dubna/IAP N.Novg.-[493-500]	29.3	0.11	60	TE <sub>11</sub> <sup>c</sup>	6	5(4)		0.8	0.15(0.2)	Ind. LINAC	0.2	oscillator
	30.74	0.12	60	TM <sub>11</sub> <sup>r</sup> /TE <sub>11</sub> <sup>c</sup>	48	35(30)		0.8	0.17(0.02)	Ind. LINAC	0.15	oscillator
	38.2	0.06	60	TM <sub>12</sub> <sup>r</sup> /TE <sub>11</sub> <sup>c</sup>	3	3(2)		0.8	0.15(0.2)	Ind. LINAC	0.2	oscillator
ILE Osaka [501]	35	0.19	72	TE <sub>11</sub> <sup>c</sup>	30	10		1.5	0.2	Ind. LINAC	0.2	oscillator
	250	0.05	30	TE <sub>11</sub> <sup>c</sup>	0.6	0.5	110	0.6	0.2	Ind. LINAC	0.04	amplifier
	60-110	0.71	60	TE <sub>01</sub> <sup>r</sup>	0.01	0.2		9.0	0.05	RF LINAC	4x10 <sup>-6</sup>	oscillator
ILT/ILE Osaka [502]	11.8	0.09	32.7	TM <sub>01</sub> <sup>c</sup>	3	1		0.43	0.19	Pulse Line	0.4	oscillator
ISAS, Sagamihara [503]	45	0.18	45	TE <sub>11</sub> <sup>c</sup>	6	2.9(0.4)	52	0.82	0.25(2.0)	Ind. LINAC	0.03	amplifier
JAERI, Ibaraki [504,505]	27	0.13	32	TM <sub>11</sub> <sup>c</sup>	0.001	0.15		0.4	0.0017	Electrostatic	10-30	oscillator
KAERI, Korea [506]	9.4	0.121	160	TE <sub>01</sub> <sup>r</sup>	100	12.1(5.1)	21	1.5	0.55(1.3)	Ind. LINAC	0.015	amplifier
KEK, Tsukuba [507-511]	11.2/16.4			TM <sub>02</sub> <sup>03</sup>	5	0.125		0.8	5.0	Modulator	1.0	oscil./ampl.
LANL, Los Alamos [512]	34.6	0.37	98	TE <sub>01</sub> <sup>r</sup>	1000	34(7.2)	52	3.5	0.85(4.0)	Ind. LINAC	0.02	amplifier
LNLN, Livermore [71,513-516]	140	0.17	98	TE <sub>11</sub> <sup>c</sup>	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]	$\lambda_w$ [mm]	Mode	Power [MW]	Efficiency [%]	Gain [dB]	Voltage [MV]	Current [kA]	Accelerator	Pulse-Length [ $\mu$ s]	Type
MIT, Cambridge [348,517-520]	9.3	0.02	33	TE <sub>11</sub> <sup>c</sup>	0.1	10	6	0.18	0.0055	Electrostatic	0.02	amplifier
	27.5	0.05	30	TE <sub>11</sub> <sup>c</sup>	1	10.3(6.3)	-	0.32	0.03(0.05)	Electrostatic	1	oscillator
	33.4	0.15	32	TE <sub>11</sub> <sup>c</sup>	61	27	50	0.75	0.3	Pulse Line	0.025	amplifier
	35.2	0.05	30	TE <sub>11</sub> <sup>c</sup>	0.8	8.6(5.2)	26	0.31	0.03(0.05)	Electrostatic	1	amplifier
NRL, Washington D.C. [521,522]	13.2-16.6	0.1	25.4	TE <sub>11</sub> <sup>c</sup>	4.2	18	29	0.245	0.094	Modulator	1.2	amplifier
	23-31	0.06	40	TE <sub>01</sub> <sup>c</sup>	4	3		0.7	0.2	Ind. LINAC	0.035	amplifier
	35	0.14	30	TE <sub>11</sub> <sup>c</sup>	17	3.2	50	0.9	0.6	Pulse Line	0.02	amplifier
	75	0.08	30	TE <sub>11</sub> <sup>c</sup>	75	6	50	1.25	1.0	Pulse Line	0.02	superrad.
NSWC/MRC, Wash. D.C. [109]	95	0.2	100		10	4		2.5	0.1	Pulse Line	0.25	oscillator
RI, Moscow [523]	6-25	0.03	48	TE <sub>11</sub> <sup>c</sup> /TM <sub>01</sub> <sup>c</sup>	10	1.7		0.6	1	Pulse Line	2	spn. emiss.
SIAB, Chengdu [524]	37	0.125	34.5	TE <sub>11</sub> <sup>c</sup>	7.6	5.4		0.5	0.28	Electrostatic	0.015	oscillator
SIOFM, Shanghai [525,526]	37.5	0.12	21	TE <sub>11</sub> <sup>c</sup>	12	3.7	50	0.4	0.8	Pulse Line	0.02	amplifier
	39	0.126	22	TM <sub>01</sub> <sup>c</sup>	14	4.4		0.4	0.8	Pulse Line	0.02	oscillator
	83-95	0.15	10	TE <sub>11</sub> <sup>c</sup> /TM <sub>01</sub> <sup>c</sup>	1	0.7		0.35	0.4	Pulse Line	0.02	spn. emiss.
TRW, Redondo Beach [527]	35	0.16	20	TE <sub>01</sub> <sup>r</sup>	0.1	9.2		0.3	0.004	Electrostatic	10	oscillator
	35	0.16	20	TE <sub>01</sub> <sup>r</sup>	0.002	6.9	3	0.29	0.0001	Electrostatic	10	amplifier
UESTC, Chengdu [528,529]	90	Smith-Purcell		TEM <sub>00</sub>	0.03	0.03		0.46	0.2	Pulse Line	0.015	oscillator
UNIV. Liverpool [110]	8-12.4	0.1	30	TE <sub>10</sub> <sup>r</sup>	2x10 <sup>-5</sup>	0.9		0.12	1.8x10 <sup>-5</sup>	Electrostatic	CW	oscillator
	9.9	0.017	19	TE <sub>10</sub> <sup>r</sup>	10 <sup>-6</sup>	0.2	18	0.05	1x10 <sup>-5</sup>	Electrostatic	CW	amplifier
UNIV. Maryland [512,530,531]	35	CHI-wiggler	64	TE <sub>01</sub> <sup>comax</sup>	0.0038	0.018	5	0.0011	0.0019	Electrostatic	1	amplifier
	86	0.38	9.6	TE <sub>01</sub> <sup>r</sup>	0.25	3.3	24	0.45	0.017	Pulse Line	0.02	amplifier
UCSB Santa Barbara [532]	120-880	0.15	71.4		0.027	0.5		2-6	0.002	Electrostatic	1-20	oscillator
UNIV. Strathelyde [533,534]	8-18	0.2	45	TE <sub>11</sub> <sup>c</sup>	1	5.7	23	0.35	0.050	Pulse Line	0.08	amplifier
UNIV. Strath., IAP [535-537]	32.5	0.13	23	TE <sub>11</sub> <sup>c</sup>	0.5	5.0		0.3	0.03	Pulse Line	0.1	oscillator
UNIV. Tel-Aviv [538-542]	4.5	0.03	44.4	TE <sub>01</sub> <sup>r</sup>	0.0035	6.3		0.07	0.0008	Electrostatic	3	oscillator
	70-110	0.2	44.4	HE <sub>10</sub> <sup>(c)</sup>	0.01	0.7(0.5)		1.1-1.5	0.001(0.0014)	Electrostatic	30000	oscillator
UNIV. Twente [543]	35	0.19	30	TE <sub>11</sub> <sup>c</sup> /TM <sub>01</sub> <sup>c</sup>	2.3	0.6		0.5	0.75	Pulse Line	0.1	spn. emiss.

r: rectangular waveguide;

c: circular waveguide

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

**Electron beam line**

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 <sup>2</sup>
waveguide mode :	HE <sub>11</sub>
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 <sup>1)</sup> :	130 - 260 GHz
on-line tunability <sup>2)</sup> :	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 [100-108].

## 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 a and continuous frequency tunability and the possibility of high unit power but the gyromonotron is a much simpler device. Up to now, the cylindrical cavity gyrotron is the only millimeter wave source which has had an extensive on-the-field experience during fusion plasma heating experiments over a wide range of frequencies and power levels (8-160 GHz, 0.1-1.0 MW).

	Gyrotron Oscillator (cyclotron resonance maser axial magnetic field)	Free Electron Maser Oscillator (periodic transverse magnetic field)
1. Beam voltage	low (70 - 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%) $\Delta B$ : slow step tuning (35%)	$\Delta U_{\text{beam}}$ : 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 <sup>2</sup>	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 / 10 s 0.5 MW / 180 s (coax. 2.2 MW / 5 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%
17. Physical size	3 m x 3 m x 3 m	12 m x 3 m x 3 m
18. Power per unit (140 GHz)	1 MW (coax., 2.5 MW)	5 MW

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

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## References

- [1] Gaponov-Grekhov, A.V., Granatstein, V.L., 1994, Application of high-power microwaves. Artech House, Boston, London.
- [2] Thumm, M., 1997, Applications of high-power microwave devices, in "Generation and Application of High Power Microwaves". R.A. Cairns and A.D.R. Phelps, eds., Institute of Physics Publishing, Bristol and Philadelphia, 305-323.
- [3] Thumm M., 2001, Novel applications of millimeter and submillimeter wave gyro-devices. *Int. J. Infrared and Millimeter Waves*, **22**, 377-386.
- [4] Flyagin, V.A., Gaponov, A.V., Petelin, M.I., Yulpatov, V.K., 1977, The gyrotron. *IEEE Trans. Microwave Theory and Techniques*, **MTT-25**, 514-521.
- [5] Andronov, A.A., Flyagin, V.A., Gaponov, A.V., Goldenberg, A.L., Petelin, M.I., Usov, V.G., Yulpatov, V.K., 1978, The gyrotron: high power sources of millimetre and submillimetre waves. *Infrared Physics*, **18**, 385-393.
- [6] Petelin, M.I., 1993, Physics of advanced gyrotrons. *Plasma Phys. and Contr. Nucl. Fusion*, **35**, Supplement B, 343-351.
- [7] Flyagin, V.A., Goldenberg, A.L., Nusinovich, G.S., 1984, Powerful gyrotrons, in *Infrared and Millimeter Waves*, **Vol. 11**, ed. K.J. Button, Academic Press, New York, 179-226.
- [8] Flyagin, V.A., Nusinovich, G.S., 1988, Gyrotron oscillators. *Proceedings of the Institute of Electrical and Electronics Engineers*, **76**, 644-656 and, 1985, Powerful gyrotrons for thermonuclear research, in *Infrared and Millimeter Waves*, **Vol. 13**, ed. K.J. Button, Academic Press, New York, 1-17.
- [9] Felch, K., Huey, H., Jory, H., 1990, Gyrotrons for ECH application. *J. Fusion Energy*, **9**, 59-75.
- [10] Goldenberg, A.L., Denisov, G.G., Zapevalov, V.E., Litvak, A.G., Flyagin, V.A., 1996, Cyclotron resonance masers: state of the art. *Radiophys. and Quantum Electronics*, **39**, 423-446.
- [11] Gold, S.H., Nusinovich, G.S., 1997, Review of high-power microwave source research. *Rev. Si. Instrum.*, **68**, 3945-3974.
- [12] Granatstein, V.L., Levush, B., Danly, B.G., Parker, R.K., 1997, A quarter century of gyrotron research and development. *IEEE Trans. on Plasma Science*, **PS-25**, 1322-1335.
- [13] Petelin, M.I., 1999, One century of cyclotron radiation. *IEEE Trans. on Plasma Science*, **PS-27**, 294-302.
- [14] Felch, K.L., Danly, B.G., Jory, H.R., Kreischer, K.E., Lawson, W., Levush, B., Temkin, R.J., 1999, Characteristics and applications of fast-wave gyrodevices. *Proc. of the IEEE*, **87**, 752-781.
- [15] Prater, R., 1990, Recent results on the application of electron cyclotron heating in tokamaks. *J. Fusion Energy*, **9**, 19-30.
- [16] Imai, T., Kobayashi, N., Temkin, R., Thumm, M., Tran, M.Q., Alkaev, V., 2001, ITER R&D: auxiliary systems: electron cyclotron heating and current drive system. *Fusion Engineering and Design*, **55**, 281-289.
- [17] Zohm, H., Gantenbein, G., Giruzzi, G., Günter, S., Leuterer, F., Maraschek, M., Meskat, J., Peeters, A.G., Suttrop, W., Wagner, D., Zabiégo, M., ASDEX Upgrade Team, ECRH Group, 1999, Experiments on neoclassical tearing mode stabilization by ECCD in ASDEX Upgrade. *Nuclear Fusion*, **39**, 577-580.
- [18] Gantenbein, G., Zohm, H., Giruzzi, G., Günter, S., Leuterer, F., Maraschek, M., Meskat, J., Yu, Q., ASDEX Upgrade Team, ECRH-Group (AUG), 2000, Complete suppression of neoclassical tearing modes with current drive at the electron-cyclotron-resonance frequency in ASDEX Upgrade tokamak. *Phys. Rev. Lett.*, **85**, 1242-1245.

- [19] Zohm, H., Gantenbein, G., Gude, A., Günter, S., Leuterer, F., Maraschek, M., Meskat, J.P., Suttrop, W., Yu, Q., ASDEX Upgrade Team, ECRH Group (AUG), 2001, The physics of neoclassical tearing modes and their stabilization by ECCD in ASDEX Upgrade. *Nuclear Fusion*, **41**, 197-202.
- [20] Zohm, H., Gantenbein, G., Gude, A., Günter, S., Leuterer, F., Maraschek, M., Meskat, J., Suttrop, W., Yu, Q., ASDEX Upgrade Team, ECRH-Group (AUG), 2001, Neoclassical tearing modes and their stabilization by electron cyclotron current drive in ASDEX Upgrade. *Physics of Plasma*, **8**, 2009-2016.
- [21] Erckmann, V., WVII-AS Team, Kasperek, W., Müller, G.A., Schüller, P.G., and Thumm, M., 1990, Electron cyclotron resonance heating transmission line and launching system for the Wendelstein VII-AS stellarator. *Fusion Technology*, **17**, 76-85.
- [22] Erckmann, V., Dammertz, G., Dorst, D., Empacher, L., Förster, W., Gantenbein, G., Geist, T., Kasperek, W., Laqua, H.P., Müller, G.A., Thumm, M., Weissgerber, H., Wobig, H., W7-X and W7-AS Teams at IPP Garching, W7-X Team at FZK Karlsruhe, W7-X Team at IPF Stuttgart, 1999, ECRH and ECCD with high power gyrotrons at the stellarators W7-AS and W7-X. *IEEE Trans. on Plasma Science*, **PS-27**, 538-546.
- [23] Kasperek, W., Erckmann, V., Laqua, H.P., Borie, E., Dammertz, G., Empacher, L., Förster, W., Gantenbein, G., Illy, S., Michel, G., Müller, G., Piończyk, B., Thumm, M., Wagner, D., Weißgerber, M., Zohm, H., W7-X and W7-AS Teams at IPP Garching, W7-X Team at IPF Stuttgart, W7-X Team at FZK Karlsruhe, 1999, ECRH and ECCD for the stellarator W7-X. *Proc. 4<sup>th</sup> Int. Workshop on Strong Microwaves in Plasmas*, Nizhny Novgorod, ed. A.G. Litvak, Inst. of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 2000, **Vol. 1**, pp. 185-204.
- [24] Erckmann, V., Laqua, H.P., Maassberg, H., Geiger, J., Dammertz, G., Kasperek, W., Thumm, M., W7-X and W7-AS teams IPP, W7-X team FZK, W7-X team IPF, 2001, Electron cyclotron resonance heating and EC-current drive experiments at W7-AS, status at W7-X. *Fusion Engineering and Design*, **53**, 365-375.
- [25] Ohkubo, K., Kubo, S., Shimosuma, T., Idei, H., Sato, M., Yoshimura, Y., Mizuno, Y., Ito, S., Kobayashi, S., Takita, Y., Kaneko, O., Kawahata, K., Komori, A., Ohyabu, N., Yamada, H., Ikeda, K., Oka, Y., Osakabe, M., Takeiri, K., Tsumori, K., Kumazawa, R., Mutoh, T., Saito, K., Seki, T., Watari, T., Ashikawa, N., Emoto, M., de Vries, P.C., Funaba, H., Goto, M., Ida, K., Inagaki, S., Isobe, M., Kado, S., Kobuchi, T., Masuzaki, S., Minami, T., Miyazawa, J., Morisaki, T., Morita, S., Murakami, S., Mutoh, S., Nagayama, Y., Nakamura, Y., Nakanishi, H., Narihara, K., Nishimura, K., Noda, N., Ohdachi, S., Ozaki, T., Pavlichenko, R.O., Peterson, B.J., Sagara, A., Sakakibara, S., Sakamoto, R., Sasao, H., Sasao, M., Sato, K., Shoji, M., Sudo, S., Suzuki, H., Takechi, M., Tanaka, K., Toi, K., Tokuzawa, T., Yamada, I., Yamaguchi, S., Yamamoto, S., Yamazaki, K., Yokoyama, M., Watanabe, K.Y., Motojima, O., Fujiwara, M., 1999, Electron cyclotron plasma production and heating on LHD: system and its application. *Proc. 4<sup>th</sup> Int. Workshop on Strong Microwaves in Plasmas*, Nizhny Novgorod, ed. A.G. Litvak, Inst. of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 2000, **Vol. 1**, pp. 27-40.
- [26] Idei, H., Kubo, S., Shimosuma, T., Sato, M., Ohkubo, K., Yoshimura, Y., Takita, Y., Kobayashi, S., Ito, S., Mizuno, Y., Tsumori, K., Ikeda, K., Notake, T., Watari, T., Kaneko, O., Komori, A., Yamada, H., de Vries, P.C., Goto, M., Ida, K., Inagaki, S., Kado, S., Kawahata, K., Kobuchi, T., Minami, T., Miyazawa, J., Morisaki, T., Morita, S., Murakami, S., Muto, S., Nagayama, Y., Nakanishi, H., Narihara, K., Peterson, B.J., Sakakibara, S., Sasao, H., Sato, K., Tanaka, K., Takeiri, Y., Watanabe, K.Y., Yamada, I., Motojima, O., Fujiwara, M., LHD Experimental Group, 2001, Electron cyclotron heating scenario and experimental results in LHD. *Fusion Engineering and Design*, **53**, 329-336.
- [27] Thumm, M., 1994, Progress in the development of high-power millimeter- and submillimeter wave gyrotrons and of free electron masers, *Archiv für Elektrotechnik* **77**, 51-55.
- [28] Thumm, M., 1995, Advanced electron cyclotron heating systems for next step fusion experiments. *Fusion Engineering and Design*, **30**, 139-170.



- [29] Thumm, M., 1997, Recent development of high power gyrotrons and windows for EC wave applications, Proc. 12<sup>th</sup> Topical Conf. on Radio Frequency Power in Plasmas, Savannah, Georgia, USA, AIP Conference Proceedings 403, pp. 183-190.  
Thumm, M., 1997, Present developments and status of electron sources for high power gyrotron tubes and free electron masers, Applied Surface Science, **111**, 106-120.
- [30] Thumm, M., 1998, State-of-the-art and recent developments of high-power gyrotron oscillators. Proc. Radio Frequency Workshop (RF 98), High Energy Density Microwaves, Pajaro Dunes, California, USA, AIP Conference Proceedings 474, pp. 146-162.
- [31] Thumm, M., Kasperek, W., 1995, Recent advanced technology in electron cyclotron heating systems. Fusion Engineering and Design, **26**, 291-317.  
Thumm, M., 1986, High power mode conversion for linearly polarized HE<sub>11</sub> hybrid mode output. Int. J. Electronics, **61**, 1135-1153.
- [32] Henle, W., Jacobs, A., Kasperek, W., Kumric, H., Müller, G.A., Schüller, P.G., Thumm, M., Engelmann, F., Rebuffi, L., 1991, Conceptual study of multi-megawatt millimeter wave transmission and antenna systems for electron cyclotron wave applications in NET/ITER. Fusion Technology **1990**, eds. B.E. Keen, M. Huguet, R. Hemsworth. Elsevier Science Publishers B.V., 238-242.
- [33] Alberti, S., Tran, M.Q., Hogge, J.P., Tran, T.M., Bondeson, A., Muggli, P., Perrenoud, A., Jödicke, B., Mathews, H.G., 1990, Experimental measurements on a 100 GHz frequency tunable quasi-optical gyrotron. Phys. Fluids, **B2**, 1654-1661.
- [34] Hogge, J.P., Tran, T.M., Paris, P.J., Tran, M.Q., 1996, Operation of a quasi-optical gyrotron with a gaussian output coupler. Phys. Plasmas, **3**, 3492-3500.
- [35] Kreisler, K.E. Temkin, R.J., 1987, Single-mode operation of a high-power, step-tunable gyrotron. Phys. Rev. Lett., **59**, 547-550.
- [36] Kurbatov, V.I., Malygin, S.A., Vasilyev, E.G., 1990, Commercial gyrotrons for thermonuclear investigations. Proc. Int. Workshop on Strong Microwaves in Plasmas, Suzdal, Inst. of Applied Physics, Nizhny Novgorod, 1991, 765-772.
- [37] Bogdanov, S.D., Kurbatov, V.I., Malygin, S.A., Orlov, V.B., Tai, E.M., 1993, Industrial gyrotrons development in Salut. Proc. 2nd Int. Workshop on Strong Microwaves in Plasmas, Moscow - Nizhny Novgorod - Moscow, ed. A.G. Litvak, Inst. of Applied Physics, Nizhny Novgorod, 1994, **Vol. 2**, 830-835.  
Zapevalov, V.E., Malygin, S.A., Pavelyev, V.G., Tsimring, Sh.E., 1984, Coupled resonator gyrotrons with mode conversion. Radiophys. Quantum Electron., **27**, 846-852.
- [38] Braz, O., Dammertz, G., Kuntze, M., Thumm, M., 1997, D-band frequency step-tuning of a 1 MW gyrotron using a Brewster output window. Int. J. Infrared and Millimeter Waves, **18**, 1465-1477.
- [39] Braz, O., Dammertz, G., Henry, S., Kuntze, M., Sato, M., Shimosuma, T., Thumm, M., 1998, Frequency step-tuned operation of a 1 MW, D-band gyrotron using a Brewster output window. Proc. 8th ITG-Conference on Displays and Vacuum Electronics, Garmisch-Partenkirchen, ITG-Fachbericht 150, pp. 299-304.
- [40] Thumm, M., Borie, E., Braz, O., Dammertz, G., Dumbrajs, O., Koppenburg, K., Kuntze, M., Piosczyk, B., 1999, 1.6 MW frequency step-tunable D-band gyrotron. Proc. 4<sup>th</sup> Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod, ed. A.G. Litvak, Inst. of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 2000, **Vol. 2**, pp. 591-609.  
Dammertz, G., Dumbrajs, O., Koppenburg, K., Piosczyk, B., Thumm, M., 2000, Frequency-step-tunable high-power gyrotrons for plasma physics applications. J. Comm. Tech. and Electronics, **45**, S60-S64.  
Dumbrajs, O., Nusinovich, G.S., 1992, Theory of a frequency-step-tunable gyrotron for optimum plasma ECRH. IEEE Trans. Plasma Science, **PS-20**, 452-457.

- [41] Thumm, M., Arnold, A., Borie, E., Braz, O., Dammertz, G., Dumbrajs, O., Koppenburg, K., Kuntze, M., Michel, G., Piosczyk, B., 2001, Frequency step-tunable (114-170 GHz) megawatt gyrotrons for plasma physics applications. *Fusion Engineering and Design*, **53**, 407-421.
- [42] Koppenburg, K., Dammertz, G., Kuntze, M., Piosczyk, B., Thumm, M., 2001, Fast frequency-step-tunable high-power gyrotron with hybrid-magnet-system. *IEEE Trans. on Electron Devices*, **ED-48**, 101-107.
- [43] Kuftin, A.N., Bogdashov, A.A., Chirkov, A.V., Denisov, G.G., Lygin, V.K., Moiseev, M.A., Zapevalov, V.E., 2001, Development of frequency step tunable 105-170 GHz 1 MW gyrotron. *Conf. Digest, 26th Int. Conf. on Infrared and Millimeter Waves*, Toulouse, France.
- [44] Golubev, S.V., Razin, S.V., Semenov, V.E., Smirnov, A.N., Vodopyanov, A.V., Zorin, V.G., 1999, Sources of soft X-rays and multicharged ions based on ECR discharge in heavy gases sustained by high-power gyrotron radiation. *Proc. 4<sup>th</sup> Int. Workshop on Strong Microwaves in Plasmas*, Nizhny Novgorod, ed. A.G. Litvak, Inst. of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 2000, **Vol. 1**, pp. 347-355.
- [45] Golubev, S.V., Luchin, V.I., Razin, S.V., Salaschenko, N.N., Smirnov, A.N., Vodopyanov, A.V., Zorin, V.G., 1999, Mirror-trapped plasma heated by powerful millimeter wave radiation as an ECR source of soft X-rays. *Proc. 4<sup>th</sup> Int. Workshop on Strong Microwaves in Plasmas*, Nizhny Novgorod, ed. A.G. Litvak, Inst. of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 2000, **Vol. 1**, pp. 356-370.
- [46] Flyagin, V.A., Kuftin, A.N., Luchinin, A.G., Nusinovich, G.S., Pankratova, T.B., Zapevalov, V.E., 1989, Gyrotrons for electron cyclotron heating and active plasma diagnostics. *Proc. Joint IAEA Techn. Committee Meeting on ECE and ECRH (EC-7 Joint Workshop)*, Hefei, P.R. China, 355-372.
- [47] Flyagin, V.A., Luchinin, A.G., Nusinovich, G.S., 1983, Submillimeter-wave gyrotrons: theory and experiment. *Int. J. Infrared and Millimeter Waves*, **4**, 629-637.
- [48] Idehara, T., Tatsukawa, T., Ogawa, I., Shimizu, Y., Nishida, N., Yoshida, K., 1996, Development and applications of submillimeter wave gyrotrons. *Proc. 3rd Int. Workshop on Strong Microwaves in Plasmas*, Nizhny Novgorod, 1997, **Vol.2**, pp. 634-659.
- [49] Ogawa, I., Iwata, M., Idehara, T., Kawahata, K., Iguchi, H., Ejiri, A., 1997, Plasma scattering measurement using a submillimeter wave gyrotron (Gyrotron FUII) as a power source. *Fusion Engineering and Design*, **34-35**, 455-458.
- [50] Shimizu, Y., Ichikawa, K., Shibutani, K., Karuhashi, K., Tatsukawa, T., Idehara, T., Ogawa, I., Okazaki, Y., Okamoto, T., 1997, Submillimetre wave gyrotron (Gyrotron FU IV) for plasma diagnostics. *Fusion Engineering and Design*, **34-35**, 459-462.
- [51] Idehara, T., Ogawa, I., Mitsudo, S., Sabchevski, S., Kitai, A., Kitai, K., 2001, Development and applications of submillimeter wave gyrotrons (FU Series). *Proc. 9th Int. Conf. Displays and Vacuum Electronics*, Garmisch-Partenkirchen, ITG-Fachbericht 165, pp. 177-182.
- [52] Bykov, Y., Goldenberg, A.F.L., Flyagin, V.A., 1991, The possibilities of material processing by intense millimeter-wave radiation. *Mat. Res. Soc. Symp. Proc.*, **169**, 41-42.
- [53] Sklyarevich, V., Detkov, A., Shevelev, M., Decker, R., 1992, Interaction between gyrotron radiation and powder materials. *Mat. Res. Soc. Symp. Proc.*, **269**, 163-169.
- [54] Link, G., Feher, L., Rhee, S., Thumm, M., Bauer, W., Ritzhaupt-Kleissl, H.-H., Weddigen, A., Böhme, R., Weisenburger, A., 1998, Sintering of ceramics using gyrotron radiation. *Proc. 8th ITG-Conference on Displays and Vacuum Electronics*, Garmisch-Partenkirchen, ITG-Fachbericht 150, pp. 375-380.
- [55] Link, G., Feher, L., Thumm, M., Ritzhaupt-Kleissl, H.-J., Böhme, R., Weisenburger, A., 1999, Sintering of advanced ceramics using a 30 GHz, 10 kW, CW industrial gyrotron. *IEEE Trans. on Plasma Science*, **PS-27**, 547-554.
- [56] Kikunaga, T., Asano, H., Yasojima, Y., Sato, F., Tsukamoto, T., 1995, A 28 GHz gyrotron with a permanent magnet system. *Int. J. Electronics*, **79**, 655-663.

- [57] Bykov, Yu., Glyavin, M., Goldenberg, A., Flyagin, V., Lygin, V., Manuilov, V., Moiseev, M., Zavolsky, N., 1999, Development and experimental investigation of high power technological gyrotrons. Conf. Digest 24<sup>th</sup> Int. Conf. on Infrared and Millimeter Waves, Monterey, California, USA, TU-A7.
- [58] Kuftin, A.N., Flyagin, V.A., Lygin, V.K., Luchinin, A.G., Malygin, O.V., Zapevalov, V.E., Zavolsky, N.A., 1999, 5.8-62 GHz CW gyrotrons with warm and permanent magnets for technological application. Proc. 4<sup>th</sup> Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod, ed. A.G. Litvak, Inst. of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 2000, **Vol. 2**, pp. 671- 676.
- [59] Kuftin, A.N., Flyagin, V.A., Lygin, V.K., Malygin, O.V., Zapevalov, V.E., Zavolsky, N.A., 1999, Technological gyrotrons with permanent magnet system. Proc. Int. University Conf. "Electronics and Radiophysics of Ultra-High Frequencies" (UHF-99), 1999, St. Petersburg, Russia, pp. 126-129.
- [60] Kuftin, A.N., Flyagin, V.A., Lygin, V.K., Malygin, O.V., Zapevalov, V.E., Zavolsky, N.A., 2000, Technological gyrotrons with permanent magnet system, 2000, Conf. Digest 25th Int. Conf. on Infrared and Millimeter Waves, Beijing, P.R. China, pp. 267-268.
- [61] Granatstein, V.L., Lawson, W., Latham, P.E., 1988, Feasibility of 30 GHz gyrokystron amplifiers for driving linear supercolliders. Conf. Digest, 13th Int. Conf. on Infrared and Millimeter Waves, Honolulu, Hawaii, Proc., SPIE **1039**, 230-231.
- [62] Granatstein, V.L., Nusinovich, G.S., 1993, On the optimal choice of microwave systems for driving TeV linear colliders. Proc. 2nd Int. Workshop on Strong Microwaves in Plasmas, Moscow - Nizhny Novgorod - Moscow, ed. A.G. Litvak, Inst. of Applied Physics, Nizhny Novgorod, 1994, **Vol. 2**, 575-586.
- [63] Granatstein, V.L., Lawson, W., 1996, Gyro-amplifiers as candidate RF drivers for TeV linear colliders. IEEE Trans. on Plasma Science, **PS-24**, 648-665.
- [64] Manheimer, W.M., Mesyats, G.A., Petelin, M.I., 1993, Super-high-power microwave radars. Proc. 2nd Int. Workshop on Strong Microwaves in Plasmas, Moscow - Nizhny Novgorod - Moscow, ed. A.G. Litvak, Inst. of Applied Physics, Nizhny Novgorod, 1994, **Vol. 2**, 632-641.
- [65] Manheimer, W.M., 1992, On the possibility of high power gyrotrons for super range resolution radar and atmospheric sensing. Int. J. Electronics, **72**, 1165-1189.
- [66] Clunie, D., Mesyats, G., Osipov, M.L., Petelin, M.I., Zagulov, P., Korovin, S.D., Clutterbuck, C.F., Wardrop, B., 1996, The design, construction and testing of an experimental high power, short-pulse radar. Proc. 3rd Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod, 1997, Vol.2, pp. 886-902.
- [67] Danly, B.G., Blank, M., Calame, J.P., Levush, B., Nguyen, K., Pershing, D., Petillo, J., Hargreaves, T.A., True, R.B., Theiss, A.J., Good, G.R., Felch, K., James, B.G., Borchard, P., Chu, T.S., Jory, H., Lawson, W.G., Antonsen, T.M., Garven, M., 1999, High average power gyrokystrons for radar applications. Conf. Digest 24<sup>th</sup> Int. Conf. on Infrared and Millimeter Waves, Monterey, California, USA, Plenary M-3.
- [68] Bratman, V.L., Denisov, G.G., Ginzburg, N.S., and Petelin, M.I., 1983, FEL's with Bragg reflection resonators. Cyclotron autoresonance masers versus ubitrons. I.E.E.E. Journal Quantum Electronics, **QE-19**, 282-296.
- [69] Marshall, T.C., 1985, Free electron lasers, MacMillan, New York.
- [70] Sprangle, P., Coffey, T., 1985, New high power coherent radiation sources, in Infrared and Millimeter Waves, **Vol. 13**, ed. K.J. Button, Academic Press, New York, 19-44.
- [71] Stone, R.R., Jong, R.A., Orzechowski, T.J., Scharlemann, E.T., Throop, A.L., Kulke, B., Thomassen, K.I., Stallard, B.W., 1990, An FEL-based microwave system for fusion. J. Fusion Energy, **9**, 77-101.
- [72] Freund, H.P., Antonsen, T.M., Jr., 1996, Principles of free-electron lasers. Chapman & Hall, London, 2nd edition.
- [73] Freund, H.P., Neil, G.R., 1999, Free-electron lasers: Vacuum electronic generators of coherent radiation. Proc. of the IEEE, **87**, 782-803.

- [74] Hirshfield, J.L., Granatstein, V.L., 1977, Electron cyclotron maser - an historical survey. *IEEE Trans. Microwave Theory Tech.*, **MTT-25**, 522-527.
- [75] Twiss, R.Q., 1958, Radiation transfer and the possibility of negative absorption in radio astronomy. *Aust. J. Phys.*, **11**, 564-579; Twiss, R.Q., Roberts, J.A., 1958, Electromagnetic radiation from electrons rotating in an ionized medium under the action of a uniform magnetic field. *Aust. J. Phys.*, **11**, 424.
- [76] Schneider, J., Stimulated emission of radiation by relativistic electrons in a magnetic field. 1959, *Phys. Rev. Lett.*, **2**, 504-505.
- [77] Gaponov, A.V., Addendum, 1959, *Izv. VUZ Radiofiz.*, **2**, 837, an addendum to Gaponov, A.V., 1959, Interaction between electron fluxes and electromagnetic waves and waveguides. *Izv. VUZ Radiofiz.*, **2**, 450-462.
- [78] Kleinwächter, H., 1950, Zur Wanderfeldröhre. *Elektrotechnik*, **4**, 245-246 (in German).
- [79] Hirshfield, J.L., Wachtel, J.M., 1964, Electron cyclotron maser. *Phys. Rev. Lett.*, **12**, 533-536.
- [80] Gaponov, A.V., Petelin, M.I. and Yulpatov, V.K., 1967, The induced radiation of excited classical oscillators and its use in high frequency electronics. *Izv. VUZ Radiofiz.* **10**, 1414 (*Radiophys. Quantum Electr.*, **10**, 794-813).
- [81] Granatstein, V.L., Alexeff, I., eds., 1987, High-power microwave sources. Artech House, Boston, London.
- [82] Benford, J. Swegle, J., 1992, High-power microwave sources. Artech House, Boston, London.
- [83] Edgcombe, C.J., ed., 1993, Gyrotron oscillators-their principles and practice. Taylor & Francis, London.
- [84] Nusinovich, G.S., 1999, Review of the theory of mode interaction in gyrodevices. *IEEE Trans. on Plasma Science*, **PS-27**, 313-326.
- [85] Pendergast, K.D., Danly, B.G., Menninger, W.L., Temkin, R.J., 1992, A long-pulse CARM oscillator experiment. *Int. J. Electronics*, **72**, 983-1004.
- [86] Galuzo, S.Yu., Kanavets, V.I., Slepikov, A.I., Pletyushkin, V.A., 1982, Relativistic cyclotron accelerator exploiting the anomalous Doppler effect. *Sov. Phys. Tech. Phys.*, **27**, 1030-1032.
- [87] Didenko, A.N., Borisov, A.R., Fomenko, G.P., Shlapakovskii, A.S., Shtein, Yu.G., 1983, Cyclotron maser using the anomalous Doppler effect. *Sov. Phys. Tech. Lett.*, **9**, 572-573.
- [88] Ogura, K., Amin, M.R., Minami, K., Zheng, X.D., Suzuki, Y., Kim, W.S., Watanabe, T., Carmel, Y., Granatstein, V.L., 1996, Experimental demonstration of a high-power slow-wave electron cyclotron maser based on a combined resonance of Cherenkov and anomalous Doppler interactions. *Phys. Rev. Lett. E*, **53**, 2726-2729.
- [89] Guo, H., Chen, L., Keren, H., Hirshfield, J.L., Park, S.Y., Chu, K.R., 1982, Measurements of gain for slow cyclotron waves on an annular electron beam. *Phys. Rev. Lett.*, **49**, 730-733.
- [90] Granatstein, V.L., Read, M.E., Barnett, L.R., 1982, Measured performance of gyrotron oscillators and amplifiers, in *Infrared and Millimeter Waves*, **Vol. 5**, ed. K.J. Button, Academic Press, New York, 267-304.
- [91] Chu, K.R., Chen, H.-Y., Hung, C.-L., Chang, T.-H., Barnett, L.R., Chen, S.-H., Yang, T.-T., Dialetis, D.J., 1999, Theory and experiment of ultrahigh-gain gyrotron traveling wave amplifier. *IEEE Trans. on Plasma Science*, **PS-27**, 391-404.
- [92] Denisov, G.G., Bratman, V.L., Phelps, A.D.R., Samsonov, S.V., 1998, Gyro-TWT with a helical operating waveguide: new possibilities to enhance efficiency and frequency bandwidth. *IEEE Trans. on Plasma Science*, **PS-26**, 508-518.
- [93] Guo, H., Chen, S.H., Granatstein, V.L., Rodgers, J., Nusinovich, G., Levush, B., Walter, M., Chen, W.J., 1997, A high performance, frequency doubling, inverted gyrotwystron. *Conf. Digest 22nd Int. Conf. on Infrared and Millimeter Waves*, Wintergreen, Virginia, USA, pp. 285-286.

- [94] Ganguly, A.K., Ahn, S., Park, S.Y., 1988, Three dimensional nonlinear theory of the gyroresonator amplifier. *Int. J. Electronics*, **65**, 597-618.
- [95] Nezhevenko, O.A., 1994, Gyrocons and magnicons: Microwave generators with circular deflection of the electron beam. *IEEE Trans. on Plasma Science*, **PS-5**, 756-772.
- [96] Hirshfield, J.L., LaPointe, M.A., Yoder, R.B., Ganguly, A.K., Wang, Ch., Hafizi, B., 1996, High-power microwave production by gyroharmonic conversion and co-generation. *Proc. 3rd Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod, 1997, Vol.2*, pp. 730-744.
- [97] Hirshfield, J.L., LaPointe, M.A., Wang, C., Ganguly, A.K., 1999, 20 GHz high-power gyroharmonic co-generation. *Proc. 4<sup>th</sup> Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod*, ed. A.G. Litvak, Inst. of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 2000, **Vol. 2**, pp. 728-739.
- [98] Phillips, R.M., 1960, The ubitron, a high-power traveling-wave tube based on a periodic beam interaction in unloaded waveguide. *IRE Trans. Electron. Dev.*, **ED-7**, 231-241 and, 1988, History of the ubitron. *Nucl. Instr. Meth.*, **A272**, 1-9, and, 1998, private communication.
- [99] Drori, R., Jerby, E., 1997, Free-electron-laser-type interaction at 1 meter wavelength range. *Nucl. Instr. Meth.*, **A393**, 284.
- [100] Verhoeven, A.G.A., Bongers, W.A., Best, R.W.B., van Ingen, A.M., Manintveld, P., Urbanus, W.H., van der Wiel, M.J., Bratman, V.L., Denisov, G.G., Shmelyov, M.Yu., Nickel, H.-U., Thumm, M., Müller, G., Kasperek, W., Pretterebner, J., Wagner, D., Caplan, M., 1992, The 1 MW, 200 GHz FOM-Fusion-FEM. *Conf. Digest 17th Int. Conf. on Infrared and Millimeter Waves, Pasadena (Los Angeles), Proc., SPIE* **1929**, 126-127.
- [101] Urbanus, W.H., Best, R.W.B., Bongers, W.A., van Ingen, A.M., Manintveld, P., Sterk, A.B., Verhoeven, A.G.A., van der Wiel, M.J., Caplan, M., Bratman, V.L., Denisov, G.G., Varfolomeev, A.A., Khlebnikov, A.S., 1993, Design of the 1 MW, 200 GHz, FOM fusion FEM. *Nucl. Instr. Meth.*, **A 331**, 235-240.
- [102] Verhoeven, A.G.A., Bongers, W.A., van der Geer, C.A.J., Manintveld, P., Schüller, F.C., Urbanus, W.H., Valentini, M., van der Wiel, M.J., 1995, A broad-tuneable free electron maser for ECW applications. *Proc. 9th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Heating, Borrego Springs, California*, 309-320.
- [103] Verhoeven, A.G.A., Bongers, W.A., Bratman, V.L., Caplan, M., Denisov, G.G., van Dijk, G., van der Geer, C.A.J., Manintveld, P., Poelmann, A.J., Pluygers, J., Shmelyov, M.Yu., Smeets, P.H.M., Sterk, A.B., Urbanus, W.H., 1998, First high power experiments with the Dutch free electron maser. *Physics of Plasmas*, **5**, 2029-2036.
- [104] Verhoeven, A.G.A., Bongers, W.A., Bratman, V.L., Caplan, M., Denisov, G.G., van der Geer, C.A.J., Manintveld, P., Poelman, A.J., Pluygers, J., Shmelyov, M.Yu., Smeets, P.H.M., Sterk, A.B., Urbanus, W.H., 1998, First microwave generation in the FOM free electron maser. *Plasma Phys. and Contr. Fusion*, **40, Suppl. 8A**, 139-156.
- [105] Verhoeven, A.G.A., Bongers, W.A., Bratman, V.L., Caplan, M., Denisov, G.G., van der Geer, C.A.J., Manintveld, P., Poelman, A.J., Plomb, J., Savilov, A.V., Smeets, P.H.M., Urbanus, W.H., 1998, First generation of mm-waves in the dutch free-electron maser. *Conf. Digest 23rd Int. Conf. on Infrared and Millimeter Waves, Colchester, UK*, pp. 21-23.
- [106] Urbanus, W.H., Bongers, W.A., van der Geer, C.A.J., Manintveld, P., Plomb, J., Pluygers, J., Poelmann, A.J., Smeets, P.H.M., Verhoeven, A.G.A., Bratman, V.L., Denisov, G.G., Savilov, V., Shmelyov, M. Yu., Caplan, M., Varfolomeev, A.A., Tolmachev, S.V., Ivanchenkov, S.N., 1999, High-power electrostatic free-electron maser as a future source for fusion plasma heating: Experiments in the short-pulse regime. *Phys. Rev. E*, **59**, 6058-6063.
- [107] Verhoeven, A.G.A., Bogers, W.A., Bratman, V.L., Caplan, M., Denisov, G.G., van der Geer, C.A.J., Manintveld, P., Poelmann, A.J., Plomb, J., Savilov, A.V., Smeets, P.H.M., Sterck, A.B., Urbanus W.H., 1999, First mm-wave generation in the FOM free electron maser. *IEEE Trans. on Plasma Science*, **PS-27**, 1084-1091.

- [108] Urbanus, W.H., Bratman, V.L., Bongers, W.A., Caplan, M., Denisov, G.G., van der Geer, C.A.J., Manintveld, P., Milityn, B., Oomens, A.A.M., Poelman, A.J., Plomp, J., Pluygers, J., Savilov, A.V., Smeets, P.H.M., Sterk, A.B., Verhoeven, A.G.A., 2001, A high power, tunable free electron maser for fusion. *Fusion Engineering and Design*, **53**, 423-430.
- [109] Freund, H.P., Granatstein, V.L., 1995, Long wavelength free electron laser in 1994. *Nucl. Instr. Meth.*, **A358**, 551-554 and, 1996, *Nucl. Instr. Meth.*, **A375**, 665-668 and, 1997, *Nucl. Instr. Meth.*, **A393**, 9-12, and, 1998, *Nucl. Instr. Meth.*, **A407**, 30-33, and, 1999 *Nucl. Instr. Meth.*, **A429**, 33-36, and private communication.
- [110] Shaw, A., Al-Shammaá, A., Stuart, R.A., Balfour, C., Lucas, J., 1996, First results of a CW industrial FEM, *Nucl. Instr. Meth.*, **A357**, 245-247.
- [111] Dylla, H.F., 1999, An overview of the user program for the Jefferson Lab free electron laser. *Proc. SPIE*, **Vol. 3618**, 388-395.  
Neil, G.R., Bohn, C.L., Benson, S.V., Biallas, G., Douglas, D., Dylla, H.F., Evans, R., Fugitt, J., Grippo, A., Gubeli, J., Hill, R., Jordan, K., Li, R., Meringa, L., Piot, P., Preble, J., Shinn, M., Siggins, T., Walker, R., Yunn, B., 2000, Sustained kilowatt lasing in a free-electron laser with same-cell energy recovery. *Phys. Rev. Lett.*, **84**, 662-665.
- [112] Mathews, H.-G., Tran, M.Q., 1991, private communication, ABB, Baden, Switzerland.
- [113] Lawrence Ives, R., Jory, H., Neilson, J., Chodorow, M., Feinstein, J., LaRue, A.D., Zitelli, L., Martorana, R., 1993, Development and test of a 500 kW, 8-GHz gyrotron. *IEEE Trans. on Electron Devices*, **ED-40**, 1316-1321.
- [114] Felch, K., Chu, T.S., Feinstein, J., Huey, H., Jory, H., Nielson, J., Schumacher, R., 1992, Long-pulse operation of a gyrotron with beam/rf separation. *Conf. Digest 17th Int. Conf. on Infrared and Millimeter Waves, Pasadena, Proc.*, SPIE **1929**, 184-195.
- [115] Chu, T.S., Blank, M., Borchard, P., Cahalan, P., Cauffman, S., Felch, K., Jory, H., Saraph, G., Wagner, D., 2000, Recent progress in producing megawatt gyrotrons for ECH applications. *Conf. Digest 25th Int. Conf. on Infrared and Millimeter Waves, Beijing, P.R. China*, pp. 13-14.
- [116] Shimozuma, T., Sato, M., Takita, Y., Kubo, S., Idei, H., Ohkubo, K., Kuroda, T., Tubokawa, Y., Huey, H., Jory, H., 1994, Development of a high power 84 GHz gyrotron. *Conf. Digest 19th Int. Conf. on Infrared and Millimeter Waves, Sendai, JSAP Catalog No.: AP 941228*, 65-66.
- [117] Sato, M., Shimozuma, T., Takita, Y., Kubo, S., Idei, H., Ohkubo, K., Kudora, T., Watari, T., Loring, Jr., M., Chu, S., Felch, K., Huey, H., 1995, Development of a high power 84 GHz gyrotron. *Conf. Digest 20th Int. Conf. on Infrared and Millimeter Waves, Lake Buena Vista (Orlando), Florida*, 195-196.
- [118] Shimozuma, T., Sato, M., Takita, Y., Ito, S., Kubo, S., Idei, H., Ohkubo, K., Watari, T., Chu, T.S., Felch, K., Cahalan, P., Loring, Jr., C.M., 1997, The first experiments on an 84 GHz gyrotron with a single-stage depressed collector. *Conf. Digest 22nd Int. Conf. on Infrared and Millimeter Waves, Wintergreen, Virginia, USA*, pp. 194-195, and private communication.
- [119] Shimozuma, T., Sato, M., Kubo, S., Idei, H., Yoshimura, Y., Takita, Y., Ito, S., Kobayashi, S., Mizuno, Y., Ohkubo, K., and LHD Experimental Group G1, G2, 1999, ECRH system and initial experiments in Large Helical Device. *Conf. Digest 24<sup>th</sup> Int. Conf. on Infrared and Millimeter Waves, Monterey, California, USA, TU-D6*.
- [120] Bogdanov, S.D., Gyrotron Team, Solujanava, E.A. 1994, Industrial gyrotrons from GYCOM. *Conf. Digest 19th Int. Conf. on Infrared and Millimeter Waves, Sendai, JSAP Catalog No.: AP 941228*, 351-352.
- [121] Goldenberg, A.L., Litvak, A.G., 1995, Recent progress of high-power millimeter wavelength gyrodevices. *Phys. Plasmas*, **2**, 2562-2572 and private communications.
- [122] Kurbatov, V.I., Malygin, S.A., Orlov, V.B., Solujanova, E.A., Tai, E.M., 1999, 70-140 GHz 1 MW gyrotrons on their way to CW operation. *Proc. 4<sup>th</sup> Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod*, ed. A.G. Litvak, Inst. of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 2000, **Vol. 2**, pp. 641-650.

- [123] Zapevalov, V.E., Manuilov, V.N., Malygin, O.V., Tsimring, Sh.E., 1994, High-power twin-beam gyrotrons operating at the second gyrofrequency harmonic. *Radiophys. and Quantum Electronics*, **37**, 237-240.
- [124] Chen, Z.-G., 1992, Luo, L., 2000, private communications, Institute of Electronics, Chinese Academy of Sciences (IEAS), Beijing, P.R. China and Guo, H., Wu, D.S., Liu, G., Miao, Y.H., Qian, S.Z., Qin, W.Z., 1990, Special complex open-cavity and low-magnetic field high power gyrotron. *IEEE Trans. on Plasma Science*, **PS-18**, 326-333.
- [125] Yao, X., Jiang, D., Feng, C., Yang, X., Zhang, H., Qi, X., Jiang, D., Li, Z., Wang, L., Zheng, S., 2000, Electron cyclotron wave current startup for ohmic discharges on the CT-6B tokamak. *IEEE Trans. on Plasma Science*, **PS-28**, 323-330.
- [126] Barroso, J.J., Castro, P.J., Pimenta, A.A., Spassov, V.A., Corrêa, R.A., Idehara, T., Ogawa, I., 1997, Operation of a 32 GHz gyrotron. *Int. J. Infrared and Millimeter Waves*, **18**, 2147-2160.
- [127] Maekawa, T., Teremuchi, Y., Yoshimura, S., Matsunaga, K., 1996, ECH system using an 88 GHz gyrotron for the WT-3 tokamak. *Proc. 11th Topical Conference on RF in Plasmas*, Palm Springs, AIP Conf. Proc., **355**, 437-440.
- [128] Idehara, T., 1995, private communication, Fukui University Japan.
- [129] Carmel, Y., Chu, K.R., Dialetis, D., Fliflet, A., Read, M.E., Kim, K.J., Arfin, B., Granatstein, V.L., 1982, Mode competition, suppression, and efficiency enhancement in overmoded gyrotron oscillators. *Int. J. on Infrared and Millimeter Waves*, **3**, 645-665.
- [130] Behm, K., Jensen, E., 1986, 70 GHz gyrotron development at Valvo. *Conf. Digest 11th Int. Conf. on Infrared and Millimeter Waves*, Pisa, 218-220.
- [131] Mourier, G., 1990, Current gyrotron development at Thomson Tubes Electroniques. *Proc. Int. Workshop on Strong Microwaves in Plasmas*, Suzdal, Inst. of Applied Physics, Nizhny Novgorod, 1991, 751-764 and, 1993, private communication.
- [132] Nagashima, T., Sakamoto, K., Maebara, S., Tsuneoka, M., Okazaki, Y., Hayashi, K., Miyake, S., Kariya, T., Mitsunaka, Y., Itoh, Y., Sugawara, T., Okamoto, T., 1990, Test results of 0.5 MW gyrotron at 120 GHz and 1.5 MW at 2 GHz Klystron for fusion application. *Proc. Int. Workshop on Strong Microwaves in Plasmas*, Suzdal, Inst. of Applied Physics, Nizhny Novgorod, 1991, 739-750 and, Okazaki, Y., 1994, private communication, Toshiba, Ohtawara, Japan.
- [133] Felch, K., Chu, T.S., DeHope, W., Huey, H., Jory, H., Nielson, J., Schumacher, R., 1994, Recent test results on a high-power gyrotron with an internal, quasi-optical converter. *Conf. Digest 19th Int. Conf. on Infrared and Millimeter Waves*, Sendai, JSAP Catalog No.: AP 941228, 333-334.
- [134] Neilson, J.M., Felch, K., Chu, T.S., Feinstein, J., Hess, C., Huey, H.E., Jory, H.R., Mizuhara, Y.M., Schumacher, R., 1995, Design and tests of a gyrotron with a radially-extracted electron beam. *IEEE Trans. on Plasma Science*, **PS-23**, 470-480.
- [135] Felch, K., Borchard, P., Chu, T.S., Jory, H., Loring, Jr., C.M., Neilson, J., Lorbeck, J.A., Blank, M., 1995, Long-pulse tests on a high-power gyrotron with an internal, quasi-optical converter. *Conf. Digest 20th Int. Conf. on Infrared and Millimeter Waves*, Lake Buena Vista (Orlando), Florida, pp. 191-192.
- [136] Felch, K., Blank, M., Borchard, P., Chu, T.S., Feinstein, J., Jory, H.R., Lorbeck, J.A., Loring, C.M., Mizuhara, Y.M., Nielson, J.M., Schumacher, R., Temkin, R.J., 1996, Long-pulse and CW tests of a 110 GHz gyrotron with an internal, quasi-optical converter. *IEEE Trans. on Plasma Science*, **PS-24**, 558-569.
- [137] Felch, K., Borchard, P., Cahalan, P., Chu, T.S., Jory, H., Loring Jr., C.M., Moeller, C.P., 1996, Status of 1 MW CW gyrotron development at CPI. *Proc. 21st Int. Conf. on Infrared and Millimeter Waves*, Berlin, AM16.
- [138] Felch, R., Borchard, P., Cauffman, S., Callis, R.W., Cahalan, P., Chu, T.S., Denison, D., Jory, H., Mizuhara, M., Remsen, D., Saraph, G., Temkin, R.J., 1998, Status report on a 110 GHz, 1 MW, CW gyrotron with a CVD diamond window. *Conf. Digest 23rd Int. Conf. on Infrared and Millimeter Waves*, Colchester, UK, pp. 376-368.

- [139] Borie, E., Dammertz, G., Gantenbein, G., Kuntze, M., Möbius, A., Nickel, H.-U., Piosczyk, B., Thumm, M., 1993, 0.5 MW/140 GHz TE<sub>10,4</sub> Gyrotron with built-in highly efficient quasioptical converter. Conf. Digest 18th Int. Conf. on Infrared and Millimeter Waves, Colchester (Essex, UK), Proc., SPIE **2104**, 519-520.  
Geist, T., Thumm, M., Wiesbeck, W., 1991, Linewidth measurement on a 140 GHz gyrotron. Conf. Digest 16th Int. Conf. on Infrared and Millimeter Waves, Lausanne, Proc., SPIE **1576**, 272-273.
- [140] Thumm, M., Borie, E., Dammertz, G., Kuntze, M., Möbius, A., Nickel, H.-U., Piosczyk, B., Wien, A., 1993. Development of high-power 140 GHz gyrotrons for fusion plasma applications. Proc. 2nd Int. Workshop on Strong Microwaves in Plasma, Moscow - Nizhny Novgorod -Moscow, Inst. of Applied Physics, Nizhny Novgorod, 1994, **Vol. 2**, 670-689.
- [141] Gantenbein, G., Borie, E., Dammertz, G., Kuntze, M., Nickel, H.-U., Piosczyk, B., Thumm, M., 1994, Experimental results and numerical simulations of a high power 140 GHz gyrotron. IEEE Trans. Plasma Science, **PS-22**, 861-870.  
Dumbrajs, O., Thumm, M., Pretterebner, J., Wagner, D., 1992, A cavity with reduced mode conversion for gyrotrons. Int. J. Infrared and Millimeter Waves, **13**, 825-840.  
Wagner, D., Gantenbein, G., Kasperek, W., Thumm, M., 1995, Improved gyrotron cavity with high quality factor. Int. J. Infrared and Millimeter Waves, **16**, 1481-1489.
- [142] Thumm, M., Borie, E., Dammertz, G., Höchtl, O., Kuntze, M., Möbius, A., Nickel, H.-U., Piosczyk, B., Semmle, C., Wien, A., 1994, Development of advanced high-power 140 GHz gyrotrons at KfK. Conf. Digest 19th Int. Conf. on Infrared and Millimeter Waves, Sendai, JSAP Catalog No.: AP 941228, 57-58.
- [143] Thumm, M., Braz, O., Dammertz, G., Iatrou, C.T., Kuntze, M., Piosczyk, B., Soudeé, G., 1995, Operation of an advanced, step-tunable 1 MW gyrotron at frequencies between 118 GHz and 162 GHz. Conf. Digest 20th Int. Conf. on Infrared and Millimeter Waves, Lake Buena Vista (Orlando), Florida, 199-200.
- [144] Dammertz, G., Braz, O., Iatrou, C.T., Kuntze, M., Möbius, A., Piosczyk, B., Thumm, M., 1995, Highly efficient long-pulse operation of an advanced 140 GHz, 0.5 MW gyrotron oscillator. Conf. Digest 20th Int. Conf. on Infrared and Millimeter Waves, Lake Buena Vista (Orlando), Florida, 285-286.
- [145] Piosczyk, B., Iatrou, C.T., Dammertz, G., Thumm, M., 1995, Operation of gyrotrons with single-stage depressed collectors. Conf. Digest 20th Int. Conf. on Infrared and Millimeter Waves, Lake Buena Vista (Orlando), Florida, 491-492.
- [146] Dammertz, G., Braz, O., Kuntze, M., Piosczyk B., Thumm, M., 1997, Step-tunable 1 MW broadband gyrotron with Brewster window. Proc. 10th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, Ameland, The Netherlands, pp. 483-488.
- [147] Dammertz, G., Braz, O., Chopra, A.K., Koppenburg, K., Kuntze, M., Piosczyk, B., Thumm, M., 1999, Recent results of the 1-MW, 140-GHz, TE<sub>22,6</sub>-mode gyrotron. IEEE Trans. on Plasma Science, **PS-27**, 330-339.
- [148] Thumm, M., Arnold, A., Borie, E., Braz, O., Dammertz, G., Dumbrajs, O., Koppenburg, K., Kuntze, M., Michel, G., Piosczyk, B., 1999, Frequency step-tunable (114-170 GHz) megawatt gyrotrons for plasma physics applications. Proc. 11<sup>th</sup> Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating (EC11), Oh-arai, Japan, October 4-8.
- [149] Agapova, M.V., Alikeev, V.V., Axenova, L.A., Bogdashov, A.A., Borshchegovsky, A.S., Keyer, A.P., Denisov, G.G., Flyagin, V.A., Fix, A.Sh., Ilyin, V.I., Ilyin, V.N., Khmara, V.A., Kostyna, A.N., Kuftin, A.N., Myasnikov, V.E., Nichiporenko, V.O., Popov, L.G., Zapevalov, V.E., Zakirov, F.G., 1995, Long-pulse 110 GHz/1MW gyrotron. Conf. Digest 20th Int. Conf. on Infrared and Millimeter Waves, Lake Buena Vista (Orlando), Florida, 205-206.



- [150] Myasnikov, V.E., Agapova, M.V., Alikae, V.V., Bogdashov, A.A., Borshegovsky, A.A., Denisov, G.G., Flyagin, V.A., Fix, A.Sh., Ilyin, V.I., Ilyin, V.N., Khmara, V.A., Khmara, D.V., Kostyna, A.N., Nichiporenko, V.O., Popov, L.G., Zapevalov, V.E., 1997, Long-pulse operation of 110 GHz 1 MW gyrotron. Conf. Digest 22nd Int. Conf. on Infrared and Millimeter Waves, Wintergreen, Virginia, USA, pp. 102-103.
- [151] Myasnikov, V.E., Agapova, M.V., Alikae, V.V., Borshchegovsky, A.S., Denisov, G.G., Flyagin, V.A., Fix, A.Sh., Ilyin, V.I., Ilyin, V.N., Keyer, A.P., Khmara, V.A., Khmara, D.V., Kostyna, A.N., Nichiporenko, V.O., Popov, L.G., Zapevalov, V.E., 1996, Megawatt power level long-pulses 110 GHz and 140 GHz gyrotrons. Proc. 3rd Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod, 1997, Vol.2, pp. 577-598.
- [152] Zapevalov, V.E., 1996, Achievement of stable operation of powerful gyrotrons for fusion. Proc. 3rd Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod, 1997, Vol.2, pp. 599-613 and private communications.
- [153] Glyavin, M.Yu., Kuftin, A.N., Venediktov, N.P., Zapevalov, V.E., 1997, Experimental investigation of a 110 GHz/1 MW gyrotron with the one-step depressed collector. Int. J. Infrared and Millimeter Waves, **18**, 2129-2136.
- [154] Myasnikov, V.E., Agapova, M.V., Nichiporenko, V.O., Popov, L.G., Usachev, S.V., Iljin, V.N., Khmara, V.A., Litvak, A.G., Denisov, G.G., Zapevalov, V.E., Flyagin, V.A., Fix, A.Sh., Alikae, V.V., Iljin, V.I., 1999, Development of 1-MW long-pulse/CW gyrotrons in 110-170 GHz frequency range. Proc. Int. University Conf. "Electronics and Radiophysics of Ultra-High Frequencies" (UHF-99), 1999, St. Petersburg, Russia, pp. 138-141.
- [155] Myasnikov, V.E., Agapova, M.V., Nichiporenko, V.O., Popov, L.G., Usachev, S.V., Iljin, V.N., Khmara, V.A., Litvak, A.G., Denisov, G.G., Zapevalov, V.E., Flyagin, V.A., Fix, A.Sh., Alikae, V.V., Iljin, V.I., 1999, Development of 1-MW long-pulse/CW gyrotrons in 110-170 GHz frequency range. Proc. 4<sup>th</sup> Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod, ed. A.G. Litvak, Inst. of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 2000, **Vol. 2**, pp. 610-614.
- [156] Denisov, G.G., 1999, Development of 1 MW output power level gyrotrons for fusion systems. Proc. 4<sup>th</sup> Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod, ed. A.G. Litvak, Inst. of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 2000, **Vol. 2**, pp. 967-986.
- [157] Denisov, G.G., Kuftin, A.N., Malygin, V.I., Venediktov, N.P., Vinogradov, D.V., Zapevalov, V.E., 1992, 110 GHz gyrotron with a built-in high-efficiency converter. Int. J. Electronics, **72**, 1079-1091.
- [158] Venediktov, N.P., Glyavin, M.Y., Zapevalov, V.E., Kuftin, A.N., 1998, Experimental study of a 110-GHz/1-MW gyrotron with a single-stage depressed collector. Radiophysics and Quantum Electronics, **41**, 449-456.
- [159] Bogdashov, A.A., Chirkov, A.V., Denisov, G.G., Kuftin, A.N., Lygin, V.K., Moiseev, M.A., Zapevalov, V.E., 2000, Development of the step tunable 140/110 GHz 1 MW gyrotron for fusion, Conf. Digest 25th Int. Conf. on Infrared and Millimeter Waves, Beijing, P.R. China, pp. 21-22, and, 2000, private communications.
- [160] Sakamoto, K., Tsuneoka, M., Maebava, S., Kasugai, A., Fujita, H., Kikuchi, M., Yamamoto, T., Nagashima, T., Kariya, T., Okazaki, Y., Shirai, N., Okamoto, T., Hayashi, K., Mitsunaka, Y., Hirata, Y., 1992, Development of a high power gyrotron for ECH of tokamak plasma. Conf. Digest 17th Int. Conf. on Infrared and Millimeter Waves, Pasadena, SPIE **1929**, 188-189.
- [161] Sakamoto, K., Tsuneoka, M., Kasugai, A., Maebara, S., Nagashima, T., Imai, T., Kariya, T., Okazaki, Y., Shirai, N., Okamoto, T., Hayashi, K., Mitsunaka, Y., Hirata, Y., 1993, Development of a high power gyrotron for fusion application in JAERI. Proc. 2nd Int. Workshop on Strong Microwaves in Plasmas, Moscow - Nizhny Novgorod - Moscow, ed. A.G. Litvak, Inst. of Applied Physics, Nizhny Novgorod, 1994, **Vol. 2**, 601-615.

- [162] Sakamoto, K., Tsuneoka, M., Kasugai, A., Takahashi, K., Maebara, S., Imai, T., Kariya, T., Okazaki, Y., Hayashi, K., Mitsunaka, Y., Hirata, Y., 1994, Development of 110 GHz CPD gyrotron. Conf. Digest 19th Int. Conf. on Infrared and Millimeter Waves, Sendai, JSAP Catalog No.: AP 941228, 63-64.
- [163] Sakamoto, K., Tsuneoka, M., Kasugai, A., Imai, T., Kariya, T., Hayashi, K., Mitsunaka, Y., 1994, Major improvement of gyrotron efficiency with beam energy recovery. Phys. Rev. Lett., **73**, 3532-3535.
- [164] Hayashi, K., Hirata, Y., Mitsunaka, Y., 1996, Startup analysis of a gyrotron power supply system for depressed-collector operation. Proc. 21st Int. Conf. on Infrared and Millimeter Waves, Berlin, AM11.
- [165] Sakamoto, K., Kasugai, A., Tsuneoka, M., Takahashi, K., Ikeda, Y., Imai, T., Kariya, T., Mitsunaka, Y., 1998, Development of high power gyrotron with diamond window. Conf. Digest 23rd Int. Conf. on Infrared and Millimeter Waves, Colchester, UK, pp. 363-364, and private communications.
- [166] Sakamoto, K., Kasugai, A., Takahashi, K., Tsuneoka, M., Ikeda, Yu., Ikeda, Yo., Imai, T., Kariya, T., Mitsunaka, Y., 1999, Status of high power gyrotron development for fusion application in JAERI. Conf. Digest 24<sup>th</sup> Int. Conf. on Infrared and Millimeter Waves, Monterey, California, USA, TU-A1.
- [167] Fujii, T., Imai, T., 1999, Development of ECRF components and system for ITER and JT-60U tokamak. Proc. 4<sup>th</sup> Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod, ed. A.G. Litvak, Inst. of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 2000, Vol. 2, pp. 615-628.
- [168] Sakamoto, K., Kasugai, A., Shoyama, H., Hayashi, K., Takahashi, K., Tsuneoka, M., Ikeda, Yu., Ikeda, Yo., Kajiwara, K., Moriyama, S., Seki, M., Fujii, T., Kariya, T., Mitsunaka, Y., Imai, T., 2000, Development of 100 GHz band gyrotrons and its application for JT-60U and ITER, Conf. Digest 25th Int. Conf. on Infrared and Millimeter Waves, Beijing, P.R. China, pp. 11-12.
- [169] Kasugai, A., Sakamoto, K., Takahashi, K., Kajiwara, K., Shoyama, H., Ikeda, Yu., Tsuneoka, M., Ikeda, Y., Fujii, T., Kariya, T., Mitsunaka, Y., Imai, T., 2001, 1 MW and long pulse operation of Gaussian beam output gyrotron with CVD diamond window for fusion devices. Fusion and Engineering and Design, **53**, 399-406.
- [170] Shimozuma, T., Kikunaga, T., Asano, H., Yasojima, Y., Miyamoto, K., Tsukamoto, T., 1993, A 120 GHz high-power whispering-gallery mode gyrotron. Int. J. Electronics, **74**, 137-151.
- [171] Asano, H., Kikunaga, T., Shimozuma, T., Yasojima, Y., Tsukamoto, T., 1994, Experimental results of a 1 Megawatt gyrotron. Conf. Digest 19th Int. Conf. Of Infrared and Millimeter Waves, Sendai, JSAP Catalog No.: AP 941228, 59-60.
- [172] Giguet, E., Dubrovin, A., Krieg, J.M., Thouvenin, Ph., Tran, C., Garin, P., Pain, M., Alberti, S., Tran, M.Q., Whaley, D.R., Borie, E., Braz, O., Möbius, A., Piosczyk, B., Thumm, M., Wien, A., 1995, Operation of a 118 GHz - 0.5 MW gyrotron with cryogenic window: design and long pulse experiments. Conf. Digest 20th Int. Conf. on Infrared and Millimeter Waves, Lake Buena Vista (Orlando), Florida, 339-340.
- [173] Alberti, S., Braz, O., Garin, P., Giguet, E., Pain, M., Thouvenin, P.H., Thumm, M., Tran, C., Tran, M.Q., 1996, Long pulse operation of a 0.5 MW - 118 GHz gyrotron with cryogenic window. Proc. 21st Int. Conf. on Infrared and Millimeter Waves, Berlin, AF1.
- [174] Pain, M., Garin, P., Tran, M.Q., Alberti, S., Thumm, M., Braz, O., Giguet, E., Thouvenin, P., Tran, C., 1996, Status of the 118 GHz - quasi-CW gyrotron of the Tore Supra and TCV tokamaks, Fusion Technology, **1996**, eds., C. Varandas, F. Serra. Elsevier Science Publishers B.V., 1997, 533-536.
- [175] Alberti, S., Arnold, A., Borie, E., Dammertz, G., Erckmann, V., Garin, P., Giguet, E., Illy, S., Le Cloarec, G., Le Goff, Y., Magne, R., Michel, G., Piosczyk, B., Thumm, M., Tran, C., Tran, M.Q., Wagner, D., 2001, European high-power CW gyrotron development for ECRH systems. Fusion Engineering and Design, **53**, 387-397.

- [176] Darbos, C., Magne, R., Alberti, S., Barbuti, A., Berger-By, G., Bouquey, F., Cara, P., Clary, J., Courtois, L., Dumont, R., Giguët, E., Gil, D., Giruzzi, G., Jung, M., Le Goff, Y., Legrand, F., Lennholm, M., Liévin, C., Peysson, Y., Roux, D., Thumm, M., Wagner, T., Tran, M.Q., Zou, X., 2000, The 118 GHz ECRH experiment on Tore Supra. 21<sup>st</sup> Symposium on Fusion Technology (SOFT 2000), Madrid, Spain, Sept. 11-15.
- [177] Magne, R., Alberti, S., Barbuti, A., Bouquey, F., Clary, J., Darbos, C., Giguët, E., Hogge, J.Ph., Jung, M., Le Goff, Y., Lennholm, M., Liévin, Ch., Portafaix, Ch., Roux, D., Saoutic, B., Thumm, M., 2001, Very long pulse testing of the TH 1506 B 118 GHz gyrotron. Proc. 14<sup>th</sup> Top. Conf. on Radio Frequency Power in Plasmas, Oxnard, California, May 7-9.
- [178] Borie, E., Gantenbein, G., Jödicke, B., Dammertz, G., Dumbrajs, O., Geist, T., Hochschild, G., Kuntze, M., Nickel, H.-U., Piosczyk, G., Thumm, M., 1992, Mode competition using TE<sub>03</sub> gyrotron cavities, *Int. J. Electronics*, **72**, 687-720.
- [179] Gantenbein, G., Borie, E., Möbius, A., Piosczyk, B., Thumm, M., 1991, Design of a high-power 140 GHz gyrotron oscillator operating in an asymmetric volume mode at KfK. Conf. Digest 16th Int. Conf. on Infrared and Millimeter Waves, Lausanne, Proc., SPIE **1576**, 264-265.
- [180] Piosczyk, B., Kuntze, M., Borie, E., Dammertz, G., Dumbrajs, O., Gantenbein, G., Möbius, A., Nickel H.-U., Thumm, M., 1992, Development of high power 140 GHz gyrotrons at KfK for applications in fusion. *Fusion Technology* **1992**, eds. C. Ferro, M. Gasparotto, H. Knoepfel. Elsevier Science Publishers B.V., 1993, 618-622.
- [181] Gantenbein, G., Borie, E., Dumbrajs, O., Thumm, M., 1995, Design of a high order volume mode cavity for a 1 MW/140 GHz gyrotron. *Int. J. Electronics*, **78**, 771-782.
- [182] Dammertz, G., Braz, O., Iatrou, C.T., Kuntze, M., Möbius, A., Piosczyk, B., Thumm, M., 1996, Long-pulse operation of a 0.5 MW TE<sub>10,4</sub> gyrotron at 140 GHz. *IEEE Trans. on Plasma Science*, **PS-24**, 570-578.
- [183] Piosczyk, B., Iatrou, C.T., Dammertz, G., Thumm, M., 1996, Single-stage depressed collectors for gyrotrons, *IEEE Trans. on Plasma Science*, **PS-24**, 579-585.
- [184] Dammertz, G., Braz, O., Kuntze, M., Piosczyk, B., Thumm, M., 1996, Design criteria for step tunable long-pulse gyrotrons. Proc. 3rd Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod, 1997, Vol.2, pp. 660-666.
- [185] Dammertz, G., Braz, O., Kuntze, M., Piosczyk, B., Thumm, M., 1997, Influence of window reflections on gyrotron operation. Conf. Digest 22nd Int. Conf. on Infrared and Millimeter Waves, Wintergreen, Virginia, USA, pp. 150-151.
- [186] Kuntze, M., Borie, E., Dammertz, G., Piosczyk, B., Thumm, M., 1999, 140 GHz gyrotron with 2.1 output power. Conf. Digest 24<sup>th</sup> Int. Conf. on Infrared and Millimeter Waves, Monterey, California, USA, W-A6.
- [187] Dammertz, G., Borie, E., Iatrou, C.T., Kuntze, M., Piosczyk, B., Thumm, M.K, 2000, 140-GHz gyrotron with multimewatt output power, *IEEE Trans. on Plasma Science*, **PS-28**, 561-566.
- [188] Piosczyk, B., Borie, E., Braz, O., Dammertz, G., Iatrou, C.T., Illy, S., Kern, S., Kuntze, M., Kartikeyan, M.V., Michel, G., Möbius, A., Thumm, M., 1996, Advanced high power gyrotrons for ECW application, *Fusion Technology* **1996**, eds., C. Varandas, F. Serra. Elsevier Science Publishers B.V., 1997, 545-548.
- [189] Kuntze, M., Borie, E., Braz, O., Dammertz, G., Illy, S., Michel, G., Möbius, A., Piosczyk, B., Thumm, M., 1998, Advanced high power gyrotrons for ECRH applications. Proc. 20th Int. Symp. on Fusion Technology (SOFT), Marseille, France, Vol. 1, pp. 489-492.
- [190] Piosczyk, B., Arnold, A., Borie, E., Dammertz, G., Drumm, O., Dumbrajs, O., Illy, S., Kuntze, M., Koppenburg, K., Schmid, M., Thumm, M., 2001, Progress in the development of advanced high power gyrotrons. Proc. 2<sup>nd</sup> IEEE Int. Vacuum Electronics Conf. (IVEC 2001), Noordwijk, Netherlands, pp. 327-330.

- [191] Piosczyk, B., Arnold, A., Borie, E., Dammertz, G., Drumm, O., Dumbrajs, O., Illy, S., Kuntze, M., Koppenburg, K., Schmid, M., Thumm, M., 2001, Advanced high power gyrotrons for fusion applications. Proc. 9<sup>th</sup> Int. Conf. Displays and Vacuum Electronics, Garmisch-Partenkirchen, ITG-Fachbericht 165, pp. 149-152.
- [192] Piosczyk, B., Arnold, A., Borie, E., Dammertz, G., Drumm, O., Dumbrajs, O., Illy, S., Kuntze, M., Koppenburg, K., Thumm, M., 2001, Development of advanced high power gyrotrons at Forschungszentrum Karlsruhe. Frequenz, **55**, 242-246.
- [193] Dammertz, G., Alberti, S., Arnold, A., Borie, E., Erckmann, V., Förster, W., Gantenbein, G., Garin, P., Giguet, E., Illy, S., Kasperek, W., Laqua, H., Le Cloarec, G., Le Goff, Y., Leonhardt, W., Magne, R., Michel, G., Müller, G., Kuntze, M., Piosczyk, B., Schmid, M., Thumm, M., Tran, M.Q., 2001, 1 MW, 140 GHz, CW gyrotron for Wendelstein 7-X. Proc. 9<sup>th</sup> Int. Conf. Displays and Vacuum Electronics, Garmisch-Partenkirchen, ITG-Fachbericht 165, pp. 143-147.
- [194] Dammertz, G., Alberti, S., Arnold, A., Borie, E., Erckmann, V., Gantenbein, G., Giguet, E., Hogge, J.-P., Illy, S., Kasperek, W., Koppenburg, K., Laqua, H., Le Cloarec, G., Le Goff, Y., Leonhardt, W., Liévin, Ch., Magne, R., Michel, G., Müller, G., Neffe, G., Kuntze, M., Piosczyk, B., Schmid, M., Thumm, M., Tran, M.Q., 2001, Development of a 140 GHz, 1 MW, continuous wave gyrotron for the W7-X stellarator. Frequenz, **55**, 270-275.
- [195] Myasnikov, V.E., Cayer, A.P., Bogdanov, S.D., Kurbatov, V.I., 1991, Soviet industrial gyrotrons. Conf. Digest 16th Int. Conf. on Infrared and Millimeter Waves, Lausanne, SPIE **1576**, 127-128.
- [196] Flyagin, V.A., Goldenberg, A.L., Zapevalov, V.E., 1993, State of the art of gyrotron investigation in Russia. Conf. Digest 18th Int. Conf. on Infrared and Millimeter Waves, Colchester (Essex, UK), Proc., SPIE **2104**, 581-584.
- [197] Denisov, G.G., Flyagin, V.A., Goldenberg, A.L., Khizhnyak, V.I., Kuftin, A.N., Malygin, V.I., Pavelyev, A.B., Pylin, A.V., Zapevalov, V.E., 1991, Investigation of gyrotrons in IAP. Conf. Digest 16th Int. Conf. on Infrared and Millimeter Waves, Lausanne, SPIE **1576**, 632-635.
- [198] Agapova, M.V., Axenova, L.A., Alikae, V.V., Cayer, A.P., Denisov, G.G., Flyagin, V.A., Fix, A.Sh., Iljin, V.I., Ilyin, V.N., Khmara, V.A., Kostyna, A.N., Kuftin, A.N., Mjasnikov, V.E., Popov, L.G., Zapevalov, V.E., 1994, Long-pulsed 140 GHz/0.5 MW gyrotron: problems and results. Conf. Digest 19th Int. Conf. on Infrared and Millimeter Waves, Sendai, JSAP Catalog No.: AP 941228, 79-80.
- [199] Mjasnikov, V.E., Agapova, M.V., Alikae, V.V., Borshchegovsky, A.S., Denisov, G.G., Fljagin, V.A., Fix, A.Sh., Ilyin, V.I., Ilyin, V.N., Keyer, A.P., Khmara, V.A., Khmara, D.V., Kostyna, A.N., Nichiporenko, V.O., Popov, L.G., Zapevalov, V.E., 1996, Megawatt power long-pulse 140 GHz gyrotron. Proc. 21st Int. Conf. on Infrared and Millimeter Waves, Berlin, ATh1.
- [200] Zapevalov, V.E., Alikae, V.V., Denisov, G.G., Flyagin, V.A., Fix, A.Sh., Kuftin, A.N., Kurbatov, V.I., Myasnikov, V.E., 1997, Development of 1 MW output power level gyrotron for ITER. Conf. Digest 22nd Int. Conf. on Infrared and Millimeter Waves, Wintergreen, Virginia, USA, pp. 108-109.
- [201] Denisov, G.G., Flyagin, V.A., Kuftin, A.N., Lygin, V.K., Moiseev, M.A., Zapevalov, V.E., 1996, Development of the prototype 170 GHz/ 1 MW gyrotron for ITER at IAP. Proc. 3rd Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod, 1997, Vol. 2, pp. 717-722.

- [202] Myasnikov, V.E., Agapova, M.V., Kostyna, A.N., Popov, L.G., Denisov, G.G., Bogdashov, A.A., Zapevalov, V.E., 1998, Development of 140 GHz/ 1 MW gyrotron with a dual RF beam output. Conf. Digest 23rd Int. Conf. on Infrared and Millimeter Waves, Colchester, UK, pp. 375-376.
- Myasnikov, V.E., Agapova, M.V., Ilyin, V.N., Khmara, D.V., Kostyna, A.N., Nichiporenko, V.O., Popov, L.G., Zakirov, F.G., Shamanova, N.A., Alikae, V.V., Ilyin, V.I., Denisov, G.G., Zapevalov, V.E., Bogdashov, A.A., Kuftin, A.N., Lygin, V.K., Litvak, A.G., Chirkov, A.V., Moiseev, M.A., 2001, Status of the 140 GHz / 800 kW / 3-10 s gyrotron for textor tokamak. Proc. 2<sup>nd</sup> IEEE Int. Vacuum Electronics Conf. (IVEC 2001), Noordwijk, Netherlands, pp. 321-323.
- [203] Myasnikov, V.E., Usachev, S.V., Agapova, M.V., Alikae, V.V., Denisov, G.G., Fix, A.Sh., Flyagin, V.A., Gnedenkov, A. Ph., Ilyin, V.I., Kuftin, A.N., Popov, L.G., Zapevalov, V.E., 1998, Long-pulse operation of 170 GHz/1 MW gyrotron for ITER. Conf. Digest 23rd Int. Conf. on Infrared and Millimeter Waves, Colchester, UK, pp. 24-25.
- [204] Myasnikov, V.E., Litvak, A.G., Usachev, S.V., Popov, L.G., Agapova, M.V., Alikae, V.V., Denisov, G.G., Gnedenkov, A. Ph., Ilyin, V.I., Ilyin, V.N., Khmara, D.V., Kostyna, A.N., Nichiporenko, V.O., Zapevalov, V.E., 1999, Development of 170 GHz gyrotron with depressed collector and diamond window for ITER. Conf. Digest 24<sup>th</sup> Int. Conf. on Infrared and Millimeter Waves, Monterey, California, USA, TU-A8.
- [205] Zapevalov, V.E., Denisov, G.G., Flyagin, V.A., Fix, A.Sh., Kuftin, A.N., Litvak, A.G., Agapova, M.V., Iljin, V.N., Khmara, V.A., Myasnikov, V.E., Nichiporenko, V.O., Popov, L.G., Usachev, S.V., Alikae, V.V., Iljin, V.I., 2001, Development of 170 GHz / 1 MW Russian gyrotron for ITER. Fusion Engineering and Design, **53**, 377-385.
- [206] Sakamoto, K., Kasugai, A., Tsuneoka, M., Takahashi, K., Imai, T., Kariya, T., Okazaki, Y., Hayashi, K., Mitsunaka, Y., Hirata, Y., 1995, Development of 170 GHz gyrotron for ITER, Conf. Digest 20th Int. Conf. on Infrared and Millimeter Waves, Lake Buena Vista (Orlando), Florida, 269-270.
- [207] Sakamoto, K., Kasugai, A., Tsuneoka, M., Takahashi, K., Imai, T., Kariya, T., Okazaki, Y., Hayashi, K., Mitsunaka, Y., Hirata, Y., 1996, Development of 170 GHz high power long pulse gyrotron for ITER. Proc. 21st Int. Conf. on Infrared and Millimeter Waves, Berlin, AT1.
- [208] Sakamoto, K., Kasugai, A., Takahashi, K., Tsuneoka, M., Imai, T., Kariya, T., Hayashi, K., 1996, Stable, single-mode oscillation with high-order volume mode at 1 MW, 170 GHz gyrotron. J. of Physical Society of Japan, **65**, 1888-1890.
- [209] Sakamoto, K., Kasugai, A., Tsuneoka, M., Takahashi, K., Ikeda, Yu., Imai, T., Nagashima, T., Ohta, M., T., Kariya, T., Hayashi, K., Mitsunaka, Y., Hirata, Y., Ito, Y., Okazaki, Y., 1997, Development of 170 GHz/500 kW gyrotrons. Int. J. of Infrared and Millimeter Waves, **18**, pp. 1637-1654.
- [210] Tsuneoka, M., Fujita, H., Sakamoto, K., Kasugai, A., Imai, T., Nagashima, T., Asaka, T., Kamioka, N., Yasuda, M., Iiyama, T., Yoshida, T., Nara, H., Ishibashi, M., 1997, Development of d.c. power supply for gyrotron with energy recovery system. Fusion Eng. and Design, **36**, 461-469.
- [211] Sakamoto, K., Kasugai, A., Tsuneoka, M., Takahashi, K., Imai, T., 1999, High power 170 GHz gyrotron with synthetic diamond window. Rev. Sci. Instrum., **70**, 208-212.
- [212] Sakamoto, K., Hayashi, K., Shoyama, H., Kasugai, A., Takahashi, K., Tsuneoka, M., Ikeda, Y., Kariya, T., Mitsunaka, T., Imai, T., 2001, Development of 170 GHz long pulse gyrotron for ITER. Conf. Digest, 26th Int. Conf. on Infrared and Millimeter Waves, Toulouse, France.
- [213] Hayashi, K., Mitsunaka, Y., Hirata, Y., Kariya, T., Okazaki, Y., Yamazaki, C., Saito, F., 2001, Design and tests of 168-GHz, 500-kW gyrotrons and power supply system. Fusion Engineering and Design, **53**, 457-464.

- [214] Flyagin, V.A., Khishnyak, V.I., Manuilov, V.N., Pavelyev, A.B., Pavelyev, V.G. Piosczyk, B., Dammertz, G., Höchtl, O., Iatrou, C., Kern, S., Nickel, H.-U., Thumm, M., Wien, A., Dumbrajs, O., 1994, Development of a 1.5 MW coaxial gyrotron at 140 GHz. Conf. Digest 19th Int. Conf. on Infrared and Millimeter Waves, Sendai, JSAP Catalog No.: AP 941228, 75-76.
- [215] Piosczyk, B., Braz, O., Dammertz, G., Iatrou, C.T., Kern, S., Möbius, A., Thumm, M., Wien, A., Zhang, S.C., Flyagin, V.A., Khishnyak, V.I., Kuftin, A.N., Manuilov, V.N., Pavelyev, A.B., Pavelyev, V.G., Postnikova, A.N., Zapevalov, V.E., 1995, Development of a 1.5 MW, 140 GHz coaxial gyrotron. Conf. Digest 20th Int. Conf. on Infrared and Millimeter Waves, Lake Buena Vista (Orlando), Florida, 423-424.
- [216] Piosczyk, B., Braz, O., Dammertz, G., Iatrou, C.T., Kern, S., Kuntze, M., Möbius, A., Thumm, M., Flyagin, V.A., Khishnyak, V.I., Kuftin, A.N., Malygin, V.I., Pavelyev, A.B., Zapevalov, V.E., 1996, A 140 GHz, 1.5 MW,  $TE_{28,16}$ -coaxial cavity gyrotron. Proc. 21st Int. Conf. on Infrared and Millimeter Waves, Berlin, AM2.
- [217] Iatrou, C.T., Braz, O., Dammertz, G., Kern, S., Kuntze, M., Piosczyk, B., Thumm, M., 1996, Operation of a megawatt coaxial gyrotron at 165 GHz. Proc. 21st Int. Conf. on Infrared and Millimeter Waves, Berlin, ATh15.
- [218] Thumm, M., Braz, O., Dammertz, G., Iatrou, C.T., Kern, S., Kuntze, M., Möbius, A., Piosczyk, B., Flyagin, V.A., Khishnyak, V.I., Malygin, V.I., Pavelyev, A.B., Zapevalov, V.E., 1996, Experimental results of 1.5 MW coaxial cavity gyrotrons in the frequency range 115-170 GHz. Proc. 3rd Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod, 1997, Vol.2, pp. 614-633.
- [219] Piosczyk, B., Braz, O., Dammertz, G., Iatrou, C.T., Kern, S., Kuntze, M., Michel, G., Möbius, A., Thumm, M., Flyagin, V.A., Khishnyak, V.I., Pavelyev, A.B., Zapevalov, V.E., 1997, Operation of a coaxial gyrotron with a dual RF-beam output. Conf. Digest 22nd Int. Conf. on Infrared and Millimeter Waves, Wintergreen, Virginia, USA, pp. 114-115.
- [220] Piosczyk, B., Braz, O., Dammertz, G., Iatrou, C.T., Kern, S., Kuntze, M., Möbius, A., Thumm, M., Flyagin, V.A., Khishnyak, V.I., Malygin, V.I., Pavelyev, A.B., Zapevalov, V.E., 1997, A 1.5-MW, 140-GHz,  $TE_{28,16}$ -coaxial cavity gyrotron. IEEE Trans. on Plasma Science, **PS-25**, 460-469.
- [221] Iatrou, C.T., Braz, O., Dammertz, G., Kern, S., Kuntze, M., Piosczyk, B., M. Thumm, 1997, Design and experimental operation of a 165-GHz, 1.5-MW, coaxial-cavity gyrotron with axial rf output. IEEE Trans. on Plasma Sciences, **PS-25**, 470-479.
- [222] Piosczyk, B., Braz, O., Dammertz, G., Iatrou, C.T., Illy, S., Kuntze, M., Michel, G., Möbius, A., Thumm, M., Flyagin, V.A., Khishnyak, V.I., Pavelyev, A.B., Zapevalov, V.E., 1998, Coaxial cavity gyrotron with dual RF beam output. IEEE Trans. on Plasma Science, **PS-26**, 393-401.
- [223] Piosczyk, B., Braz, O., Dammertz, G., Iatrou, C.T., Kuntze, M., Michel, G., Möbius, A., Thumm, M., 1998, 165 GHz,  $TE_{31,17}$  - coaxial cavity gyrotron with quasi-optical RF-output. Conf. Digest 23rd Int. Conf. on Infrared and Millimeter Waves, Colchester, UK, pp. 168-169.
- [224] Piosczyk, B., Braz, O., Dammertz, G., Iatrou, C.T., Illy, S., Kuntze, M., Michel, G., Thumm, M., 1999, 165 GHz, 1.5 MW-Coaxial cavity gyrotron with depressed collector. IEEE Trans. on Plasma Science, **PS-27**, 484-489.
- [225] Dumbrajs, O., Khishnyak, V.I., Pavelyev, A.B., Piosczyk, B., Thumm, M., 1999, Design of rapid frequency-step-tunable powerful coaxial-cavity harmonic gyrotrons. Conf. Digest 24<sup>th</sup> Int. Conf. on Infrared and Millimeter Waves, Monterey, California, USA, TU-A6.
- Dumbrajs, O., Anderer, J., Illy, S., Piosczyk, B., Thumm, M., Zavolsky, N.A., 1999, Multifrequency operation of a gyrotron. IEEE Trans. on Plasma Science, **PS-27**, 327-329.

- [226] Piosczyk, B., Braz, O., Dammertz, G., Kuntze, M., Michel, G., Lamba, O.S., Thumm, M., 1999, Progress report on the 165 GHz coaxial cavity gyrotron. Conf. Digest 24<sup>th</sup> Int. Conf. on Infrared and Millimeter Waves, Monterey, California, USA, TU-A9.  
Michel, G., Kuntze, M., Piosczyk, B., Thumm, M., 1999, Considerations on multimode quasi-optical converters. Conf. Digest 24<sup>th</sup> Int. Conf. on Infrared and Millimeter Waves, Monterey, California, USA, PS-8.
- [227] Piosczyk, B., Braz, O., Dammertz, G., Kuntze, M., Michel, G., Thumm, M., 1999, Status of the 1.5 MW, 165 GHz coaxial cavity gyrotron. Proc. 4<sup>th</sup> Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod, ed. A.G. Litvak, Inst. of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 2000, **Vol. 2**, pp. 629-634.
- [228] Piosczyk, B., Arnold, A., Dammertz, G., Dumbrajs, O., Kuntze, M., Leonhardt, W., Pavelyev, A.B., Schmid, M., Thumm, M., 2000, 2.2 MW, 165 GHz coaxial cavity gyrotron, Conf. Digest 25<sup>th</sup> Int. Conf. on Infrared and Millimeter Waves, Beijing, P.R. China, pp. 19-20.
- [229] Piosczyk, B., Arnold, A., Dammertz, G., Kuntze, M., Michel, G., Lamba, O.S., Thumm, M.K., 2000, Step-frequency operation of a coaxial cavity from 134 to 169.5 GHz. IEEE Trans. on Plasma Science, **PS-28**, 918-923.
- [230] Dumbrajs, O., Khizhnyak, V.I., Pavelyev, A.B., Piosczyk, B., Thumm, M.K., 2000, Design of rapid-frequency step-tunable powerful coaxial-cavity harmonic gyrotrons. IEEE Trans. on Plasma Science, **PS-28**, 681-687.
- [231] Ling, G., B. Piosczyk, M. K. Thumm: A new approach for a multistage depressed collector for gyrotrons. IEEE Trans. on Plasma Science, PS-28, 606-613 (2000).
- [232] Vlasov, S.N., Zagryadskaya, L.I., Orlova, I.M., 1976, Open coaxial resonators for gyrotrons. Radio Eng. Electron. Phys., **21**, 96-102.
- [233] Gaponov, A.V., Flyagin, V.A., Goldenberg, A.L., Nusinovich, G.S., Tsimring, Sh.E., Usov, V.G., Vlasov, S.N., 1981, Powerful millimeter-wave gyrotrons. Int. J. Electronics, **51**, 277-302.
- [234] Flyagin, V.A., Khizhnyak, V.I., Kuftin, A.N., Manuilov, V.N., Pavelyev, A.B., Pavelyev, V.G., Zapevalov, V.E., 1997. Investigation of coaxial gyrotrons at IAP RAS, Conf. Digest 22<sup>nd</sup> Int. Conf. on Infrared and Millimeter Waves, Wintergreen, Virginia, USA, pp. 112-113.
- [235] Pavelyev, A.B., Flyagin, V.A., Khizhnyak, V.I., Manuilov, V.N., Zapevalov, V.E., 1999, Investigations of advanced coaxial gyrotrons at IAP RAS. Proc. Int. University Conf. "Electronics and Radiophysics of Ultra-High Frequencies" (UHF-99), 1999, St. Petersburg, Russia, pp. 142-145.
- [236] Khizhnyak, V.I., Manuilov, V.N., Pavelyev, A.B., Zapevalov, V.E., 2000, Investigations of advanced coaxial gyrotrons at IAP RAS, Conf. Digest 25<sup>th</sup> Int. Conf. on Infrared and Millimeter Waves, Beijing, P.R. China, pp. 117-118.
- [237] Zapevalov, V.E., Pavelyev, A.B., Khizhnyak, V.I., 2000, Experimental test of the natural scheme of electron beam energy recovery in a coaxial gyrotron. Radiophysics and Quantum Electronics, **43**, 671-674.
- [238] Khizhnyak, V.I., Manuilov, V.N., Pavelyev, A.B., Zapevalov, V.E., 2001, Natural scheme of electron beam energy recovery in coaxial gyrotron. Proc. 9<sup>th</sup> Int. Conf. Displays and Vacuum Electronics, Garmisch-Partenkirchen, ITG-Fachbericht 165, pp. 153-157.
- [239] Hogge, J.P., Kreischer, K.E., Read, M.E., 1995, Results of testing a 3 MW, 140 GHz gyrotron with a coaxial cavity. Conf. Digest 20<sup>th</sup> Int. Conf. on Infrared and Millimeter Waves, Lake Buena Vista (Orlando), Florida, 417-418.
- [240] Kimura, T., Hogge, J.P., Advani, R., Denison, D., Kreischer, K.E., Temkin, R.J., 1996, Investigation of megawatt power level gyrotrons for ITER. Proc. 21<sup>st</sup> Int. Conf. on Infrared and Millimeter Waves, Berlin, AM1.
- [241] Hargreaves, T.A., Fliflet, A.W., Fischer, R.P., Barsanti, M.L., 1990, Depressed collector performance on the NRL quasi-optical gyrotron. Conf. Digest 15<sup>th</sup> Int. Conf on Infrared and Millimeter Waves, Orlando, Proc., SPIE **1514**, 330-332.

- [242] Häfner, H.E., Bojarsky, E., Norajitra, P., Reiser, 1992, H. Cryocooled windows for high frequency plasma heating. *Fusion Technology 1992*, eds. C. Ferro, M. Gasparotto, H. Knoepfel (Elsevier Science Publishers B.V. 1992), pp.520-523.
- [243] Häfner, H.E., Bojarsky, E., Heckert, K., Norajitra, P., Reiser, H., 1994, Liquid nitrogen cooled window for high frequency plasma heating. *Journal of Nuclear Materials*, **212-215**, 1035-1038.
- [244] Häfner, H.E., Heckert, K., Norajitra, P., Vouriot, R. Hofmann, A., Münch, N., Nickel, H.-U., Thumm, M., Erckmann, V., 1994, Investigations of liquid nitrogen cooled windows for high power millimeter wave transmission. *Conf. Digest 19th Int. Conf. on Infrared and Millimeter Waves*, Sendai, JSAP Catalog No.: AP 941228, 281-282.
- [245] Heidinger, R., Link, G., 1995, The mm-wave absorption in sapphire and its description by the 2-phonon model. *Conf. Digest 20th Int. Conf. on Infrared and Millimeter Waves*, Lake Buena Vista (Orlando), Florida, 16-17.
- [246] Norajitra, P., Häfner, H.E., Thumm, M., 1995, Alternatives for edge cooled single disk windows with 1 MW transmission power. *Conf. Digest 20th Int. Conf. on Infrared and Millimeter Waves*, Lake Buena Vista (Orlando), Florida, 475-476.
- [247] Saitoh, Y., Itoh, K., Yoshiyuki, T., Ebisawa, K., Yokokura, K., Nagashima, T., Yamamoto, T., 1992, Cryogenic window for millimeter-wave transmission. *Fusion Technology 1992*, eds. C. Ferro, M. Gasparotto, H. Knoepfel (Elsevier Science Publishers B.V. 1992), pp. 632-636.
- [248] Kasugai, A., Yokokura, K., Sakamoto, K., Tsuneoka, M., Yamamoto, T., Imai, T., Saito, Y., Ito, K. Yoshiyuki, T., Ebisawa, K., 1994, High power tests of the cryogenic window for millimeter wave. *Conf. Digest 19th Int. Conf. on Infrared and Millimeter Waves*, Sendai, JSAP Catalog No.: AP 941228, 295-296.
- [249] Garin, P., Bon-Mardion, G., Pain, M., Heidinger, R., Thumm, M., Dubrovin, A., Giguet, E., Tran, C., 1995, Cryogenically cooled window: a new step toward gyrotron CW operation. *Conf. Digest 20th Int. Conf. on Infrared and Millimeter Waves*, Lake Buena Vista (Orlando), Florida, 271-272.
- [250] Parshin, V.V., Heidinger, R., Andreev, B.A., Gusev, A.V., Shmagin, V.B., 1995, Silicon with extra low losses for megawatt output gyrotron windows. *Conf. Digest 20th Int. Conf. on Infrared and Millimeter Waves*, Lake Buena Vista (Orlando), Florida, 22-23, and Parshin, V.V., 1998, private communication.
- [251] Shimozuma, T., Sato, M., Takita, Y., Kubo, S., Idei, H., Ohkubo, K., Watari, T., Morimoto, S., Tajima, K., 1995, Development of elongated vacuum windows for high power CW millimeter waves. *Conf. Digest 20th Int. Conf. on Infrared and Millimeter Waves*, Lake Buena Vista (Orlando), Florida, 273-274.
- [252] Shimozuma, T., Morimoto, S., Sato, M., Takita, Y., Ito, S., Kubo, S., Idei, H., Okhubo, K., Watari, T., 1997, A forced gas-cooled single disk window for high power cw millimeter waves. *Conf. Digest 22nd Int. Conf. on Infrared and Millimeter Waves*, Wintergreen, Virginia, USA, 146-147.
- [253] Petelin, M.I., Kasperek, W., 1991, Surface corrugation for broadband matching of windows in powerful microwave generators. *Int. J. Electronics*, **71**, 871-873.
- [254] Nickel, H.-U., Ambrosy, U., Thumm, M., 1992, Vacuum windows for frequency-tunable high-power millimeter wave systems. *Conf. Digest 17th Int. Conf. on Infrared and Millimeter Waves*, Pasadena, Proc., SPIE **1929**, 462-463.
- [255] Nickel, H.-U., Massler, H., Thumm, M., 1993, Development of broadband vacuum windows for high-power millimeter wave systems. *Conf. Digest 18th Int. Conf. on Infrared and Millimeter Waves*, Colchester (Essex, UK), Proc., SPIE **2104**, 172-173.
- [256] Shang, C.C., Caplan, M., Nickel, H.-U., Thumm, M., 1993, Electrical analysis of wideband and distributed windows using time-dependent field codes. *Conf. Digest 18th Int. Conf. on Infrared and Millimeter Waves*, Colchester (Essex, UK), Proc., SPIE **2104**, 178-179.



- [257] Fix, A.S., Sushilin, P.B., 1993, Calculation and experimental investigation of cryogenic window. Proc. 5th Russian-German Meeting on ECRH and Gyrotrons, Karlsruhe, pp. 389-392 and, 1994, Proc. 6th Russian-German Meeting on ECRH and Gyrotrons, Moscow, 1994, Vol. 2, pp. 244-247.
- [258] Moeller, C.P., Doane, J.L., DiMartino, M., 1994, A vacuum window for a 1 MW CW 110 GHz gyrotron. Conf. Digest 19th Int. Conf. on Infrared and Millimeter Waves, Sendai, Conf. Digest 19th Int. Conf. on Infrared and Millimeter Waves, Sendai, JSAP Catalog No.: AP 941228, 279-280.
- [259] Heidinger, R., 1994, Dielectric property measurements on CVD diamond grades for advanced gyrotron windows. Conf. Digest 19th Int. Conf. on Infrared and Millimeter Waves, Sendai, JSAP Catalog No.: AP 941228, 277-278.
- [260] Heidinger, R., Schwab, R., Spörl, R., Thumm, M., 1997, Dielectric loss measurements in CVD diamond windows for gyrotrons. Conf. Digest 22nd Int. Conf. on Infrared and Millimeter Waves, Wintergreen, Virginia, USA, 142-143.
- [261] Braz, O., Kasugai, A., Sakamoto, K., Takahashi, K., Tsuneoka, M., Imai, T., Thumm, 1997, High power 170 GHz test of CVD diamond for ECH window, Int. J. Infrared and Millimeter Waves, **18**, 1495-1503.
- [262] Thumm, M., 1998, Development of output windows for high-power long-pulse gyrotrons and EC wave applications, Int. J. Infrared and Millimeter Waves, **19**, 3-14.
- [263] Heidinger, R., Spörl, R., Thumm, M., Brandon, J.R., Sussmann, R.S., Dodge, C.N., 1998, CVD diamond windows for high power gyrotrons. Conf. Digest 23rd Int. Conf. on Infrared and Millimeter Waves, Colchester, U.K., pp. 223-225.
- [264] Kasugai, A., Sakamoto, K., Takahashi, K., Tsuneoka, M., Kariya, T., Imai, T., Braz, O., Thumm, M., Brandon, J.R., Sussmann, R.S., Beale, A., Ballington, D.C., 1998, Chemical vapor deposition diamond for high-power and long-pulse millimeter wave transmission. Rev. Scientific Instruments, **69**, 2160-2165.
- [265] Thumm, M., Braz, O., Heidinger, R., Makowski, M., Spörl, R., 1999, Design and optimization of the ITER ECRF window unit. Conf. Digest 24<sup>th</sup> Int. Conf. on Infrared and Millimeter Waves, Monterey, California, USA, PS-5.
- [266] Spörl, R., Heidinger, R., Schwab, R., 1999, Dielectric characterisation of CVD diamond windows at elevated temperatures. Conf. Digest 24<sup>th</sup> Int. Conf. on Infrared and Millimeter Waves, Monterey, California, USA, F-A9.
- [267] Thumm, M., Alberti, S., Arnold, A., Borie, E., Dammertz, G., Erckmann, V., Garin, P., Giguet, E., Illy, S., Le Cloarec, G., Le Goff, Y., Magne, R., Michel, G., Piosczyk, B., Tran, M.Q., Wagner, D., 1999, 1 MW, 140 GHz, CW gyrotron for Wendelstein-7-X. Conf. Digest 24<sup>th</sup> Int. Conf. on Infrared and Millimeter Waves, Monterey, California, USA, Plenary W-2.
- [268] Thumm, M., Arnold, A., Heidinger, R., Rohde, M., Schwab, R., Spoerl, R., 2001, Status report on CVD diamond window development for high power ECRH. Fusion Engineering and Design, **53**, 517-524.
- [269] Brandon, J.R., Coe, S.E., Sussmann, R.S., Sakamoto, K., Spoerl, R., Heidinger, R., Hanks, S., 2001, Development of CVD diamond r.f. windows for ECRH. Fusion Engineering and Design, **53**, 553-559.
- [270] Heidinger, R., Meier, A., Rohde, M., Spörl, R., Thumm, M., Arnold, A., 2000, Millimeter wave characterisation of large area MPACVD diamond windows. Conf. Digest 25th Int. Conf. on Infrared and Millimeter Waves, Beijing, P.R. China, pp. 389-390.
- [271] Petelin, M.I., 1999, Microwave applications of gratings. Proc. 4<sup>th</sup> Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod, ed. A.G. Litvak, Inst. of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 2000, **Vol. 2**, pp. 930-941.
- [272] Thumm, M., 2001, MPACVD-diamond windows for high-power and long-pulse millimeter wave transmission. Diamond and Related Materials, **10**, 1692-1699.

- [273] Heidinger, R., Meier, A., Thumm, M., 2001, Dielectric loss studies in diamond window components for megawatt gyrotrons. Proc. 2<sup>nd</sup> IEEE Int. Vacuum Electronics Conference (IVEC 2001), Noordwijk, Netherlands, pp. 227-230.
- [274] Heidinger, R., Meier, A., Thumm, M., Arnold, A., 2001, MPACVD diamond discs characterised as window components for megawatt gyrotrons. Proc. 9<sup>th</sup> Int. Conf. Displays and Vacuum Electronics, Garmisch-Partenkirchen, ITG-Fachbericht 165, pp. 357-362.
- [275] Bohlen, H., Eisen, E., Felch, K., Jory, H., Lenci, S., Wright, E., 1998, New high-power microwave tubes for scientific industrial and broadcast applications. Proc. 8th ITG-Conference on Displays and Vacuum Electronics, Garmisch-Partenkirchen, ITG-Fachbericht 150, pp. 248-256.
- Jory, H., 1997, Communications & Power Industries, Palo Alto, private communication.
- [276] Zaytsev, N.I., Pankratova, T.P., Petelin, M.I., Flyagin, V.A., 1974, Millimeter- and submillimeter-wave gyrotrons. Radio Eng. and Electronic Phys., **19**, 103-107.
- [277] Spira-Hakkarainen, S.E., Kreischer, K.E., Temkin, R.J., 1990, Submillimeter-wave harmonic gyrotron experiment. IEEE Trans. Plasma Science, **PS-18**, 334-342.
- Kreischer, K.E., Grimm, T.L., Guss, W.C., Temkin, R.J., Xu, K.Y., 1990, Research at MIT on high frequency gyrotrons for ECRH. Proc. Int. Workshop on Strong Microwaves in Plasmas, Suzdal, Inst. of Applied Physics, Nizhny Novgorod, 1991, 713-725.
- [278] Kreischer, K., Farrar, C., Griffin, R., Temkin, R., Viereg, J., 1999, The development of a 250 GHz cw gyrotron for EPR and NMR spectroscopy. Conf. Digest 24<sup>th</sup> Int. Conf. on Infrared and Millimeter Waves, Monterey, California, USA, TU-A3.
- [279] Idehara, T., Tatsukawa, T., Ogawa, I., Tanabe, H., Mori, T., Wada, S., Brand, G.F., Brennan, M.H., 1992, Development of a second cyclotron harmonic gyrotron operating at submillimeter wavelengths. Phys. Fluids **B4**, 267-273 and 1993, Phys. Fluids **B5**, 1377-1379.
- [280] Shimizu, Y., Makino, S., Ichikawa, K., Kanemaki, T. Tatsukawa, T., Idehara, T., Ogawa, I., 1995, Development of submillimeter wave gyrotron using 12 T superconducting magnet. Phys. Plasmas, **2**, 2110-2116.
- [281] Idehara, T., Shimizu, Y., Ichikawa, K., Makino, S., Shibusaki, K., Kurahashi, K., Tatsukawa, T., Ogawa, I., Okazaki, Y., Okamoto, T., 1995, Development of a medium power, submillimeter wave gyrotron using a 17 T superconducting magnet. Phys. Plasmas, **2**, 3246-3248.
- [282] Idehara, T., Tatsukawa, T., Ogawa, I., Shimizu, Y., Kurahashi, K., Nishida, N., Yoshida, K., 1996, Development of terahertz gyrotron using a 17T superconducting magnet. Proc. 21st Int. Conf. on Infrared and Millimeter Waves, Berlin, AT9.
- [283] Idehara, T., Nishida, N., Yoshida, K., Ogawa, I., Tatsukawa, T., Wagner, D., Gantenbein, G., Kasperek, W., Thumm, M., 1998, High frequency and high mode purity operations of gyrotron FU IVA, Int. J. Infrared and Millimeter Waves, **19**, 919-930.
- [284] Idehara, T., Ogawa, I., Mitsudo, S., Pereyaslavets, M.L., Tsuchida, T., Ui, M., 1998, Development of a submillimeter wave gyrotron (gyrotron FU V), Conf. Digest 23rd Int. Conf. on Infrared and Millimeter Waves, Colchester, UK, pp. 398-399.
- [285] Idehara, T., Ogawa, I., Mitsudo, S., Pereyaslavets, M., Nishida, N., Yoshida, K., 1999, Development of frequency tunable, medium power gyrotrons (Gyrotron FU Series) as submillimeter wave radiation sources. IEEE Trans. on Plasma Science, **PS-27**, 340-354.
- [286] Xu, K.Y., Kreischer, K.E., Guss, W.C., Grimm, T.L., Temkin, R.J., 1990, Efficient operation of a megawatt gyrotron. Conf. Digest 15th Int. Conf. on Infrared and Millimeter Waves, Orlando, Proc., SPIE **1514**, 324-326.
- [287] Grimm, T.L., Kreischer, K.E., Guss, W.C., Temkin, R.J., 1992, Experimental study of a megawatt 200-300 GHz gyrotron oscillator. Fusion Technology, **21**, 1648-1657 and, 1993, Phys. Fluids, **B5**, 4135-4143.

- [288] Grimm, T.L., Borchard, P.M., Kreischer, K.E., Guss, W.C., Temkin, R.J., 1992, High power operation of a 200-300 GHz gyrotron oscillator and multimegawatt gyrotrons for ITER. Conf. Digest 17th Int. Conf. on Infrared and Millimeter Waves, Pasadena, Proc., SPIE **1929**, 190-191 and 194-195.
- [289] Kimura, T., Danly, B.G., Kreischer, K.E., Temkin, R.J., 1995, Development of a 1 MW, 170 GHz gyrotron with internal mode converter. Conf. Digest 20th Int. Conf. on Infrared and Millimeter Waves, Lake Buena Vista (Orlando), Florida, 201-202.
- [290] Sirigiri, J.R., Kreischer, K.E., Machuzak, J., Mastovsky, I., Shapiro, M.A., Temkin, R.J., 2001, Photonic-band-gap resonator gyrotron. Phys. Rev. Lett., **86**, 5628-5631.
- [291] Brand, G.F., Fekete, P.W., Hong, K., Moore, K.J., Idehara, T., 1990, Operation of a tunable gyrotron at the second harmonic of the electron cyclotron frequency. Int. J. Electronics, **68**, 1099-1111.
- [292] Hong, K.D., Brand, G.F., 1993, A 150-600 GHz step-tunable gyrotron. J. Appl. Phys., **74**, 5250-5258.
- [293] Antakov, I.I., Gachev, I.G., Kurbatov, V.I., Sokolov, E.V., Solujanova, E.A., Zasytkin, E.V., 1996, A Ka-band 10 kW CW efficient compact gyrotron for materials processing. Proc. 21st Int. Conf. on Infrared and Millimeter Waves, Berlin, AM3.
- [294] Antakov, I.I., Gachev, I.G., Kurbatov, V.I., Sokolov, E.V., Solujanova, E.A., Zasytkin, E.V., 1996, Ka-band and W-band 10 kW CW high efficiency gyrotrons for materials processing. Proc. 3rd Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod, 1997, Vol.2, pp. 679-687.
- [295] Flyagin, V.A., Kuftin, A.N., Lygin, V.K., Luchinin, A.G., Malygin, O.V., Manuilov, V.N., Tsimring, Sh.E., Zapevalov, V.E., 1996, CW 10 kW technological gyrotron in the range 15-50 GHz. Proc. 3rd Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod, 1997, Vol.2, pp. 711-716.
- [296] Zasytkin, E.V., Antakov, I.I., Gachev, I.G., Vlasov, S.N., Sokolov, E.V., 1998, Continuously tunable 35-190 GHz powerful gyrotrons at GYCOM. Conf. Digest 23rd Int. Conf. on Infrared and Millimeter Waves, Colchester, UK, pp. 323-324.  
Zasytkin, E.V., Moiseev, M.A., Nemirovskaya, L.L., 1998, Expansion of a frequency tuning band in a frequency band in a gyrotron with coupled cavities, Int. J. Electronics, **85**, 207-216.
- [297] Möbius, A., 1995, A permanent magnet system for gyrotrons, 1995, Conf. Digest 20th Int. Conf. on Infrared and Millimeter Waves, Lake Buena Vista (Orlando), Florida, and Millimeter Waves, Lake Buena Vista (Orlando), Florida, 487-488.
- [298] Glyavin, M., Goldenberg, A., Flyagin, V., Kuftin, A., Luchinin, A., Lygin, V., Malygin, O., Manuilov, V., Moiseev, M., Zavolsky, N., Zapevalov, V., 1999, Experimental investigation of technological gyrotrons. Proc. Int. University Conf. "Electronics and Radiophysics of Ultra-High Frequencies" (UHF-99), 1999, St. Petersburg, Russia, p. 112.
- [299] Bykov, Yu., Glyavin, M., Goldenberg, A., Luchinin, A., Lygin, V., Zavol'skii, N., 1999, Efficient 24-30 GHz CW gyrotrons for technological applications. Proc. 4<sup>th</sup> Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod, ed. A.G. Litvak, Inst. of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 2000, **Vol. 2**, pp. 747-750.
- [300] Bykov, Y., Glyavin, M., Denisov, G., Holoptsev, V., Ereemeev, A., Plotnikov, I., Pavlov, V., 2001, 3.5 kW 24 GHz compact gyrotron system for microwave processing of materials. Proc. 8th Int. Conf. on Microwave and High Frequency Heating, Bayreuth, p. 89.
- [301] Kikunaga, T., Asano, H., Hemmi, K., Sato, F., Tsukamoto, T., 1995, A 28 GHz gyrotron with a permanent magnet system. Conf. Digest 20th Int. Conf. on Infrared and Millimeter Waves, Lake Buena Vista (Orlando), Florida, 485-486.
- [302] Takada, T., Ohashi, K., Honshima, M., Kikunaga, T., 1995, Nd-Te-B permanent magnet circuit for a 28 GHz CW gyrotron. Conf. Digest 20th Int. Conf. on Infrared and Millimeter Waves, Lake Buena Vista (Orlando), Florida, and Millimeter Waves, Lake Buena Vista (Orlando), Florida, 489-490.

- [303] Asano, H., Kikunaga, K., Hemmi, K., Sato, F., Tsukamoto, T., 1996, A 28 GHz gyrotron with a permanent magnet system for industry applications. Proc. 21st Int. Conf. on Infrared and Millimeter Waves, Berlin, AM5.
- [304] Bratman, V.L., Ginzburg, N.S., Nusinovich, G.S., Petelin, M.I., Strelkov, P.S., 1981, Relativistic gyrotrons and cyclotron autoresonance masers. *Int. J. Electronics*, **51**, 541-567.
- [305] Bratman, V.L., Denisov, G.G., Ofitserov, M.M., Korovin, S.D., Polevin, S.D., Rostov, V.V., 1987, Millimeter-wave HF relativistic electron oscillators. *IEEE Trans. on Plasma Science*, **PS-15**, 2-15.
- [306] Zaitsev, N.I., Ginzburg, N.S., Zavolskii, N.A., Zapevalov, V.E., Ilyakov, E.V., Kulagin, I.S., Kuftin, A.N., Lygin, V.K., Moiseev, M.A., Novozhilova, Yu.V., Rozental, R.M., Tsalolokhin, V.I., 2001, Highly efficient relativistic SHF gyrotron with a microsecond pulse width. *Tech. Phys. Lett.*, **27**, 266-270.
- [307] Kremontsov, V.I., Petelin, M.I., Rabinovich, M.S., Rukhadze, A.A., Strelkov, P.S., Shkvarunets, A.G., 1978, Plasma-filled gyrotron with a relativistic supervacuum electron beam, *Sov.Phys. JETP*, **48**, 1084.
- [308] Ginzburg, N.S., Kremontsov, V.I., Petelin, M.I., Strelkov, P.S., Shkvarunets, A.G., 1979, Experimental investigation on a high-current relativistic cyclotron maser. *Sov. Phys. Tech. Phys.*, **24**, 218-222.
- [309] Voronkov, S.N., Kremontsov, V.I., Strelkov, P.S., Shkvarunets, A.G., 1982, Stimulated cyclotron radiation and millimeter wavelengths from high-power relativistic electron beams, *Sov. Phys. Tech. Phys.*, **27**, 68-69.
- [310] Gilgenbach, R.M., Wang, J.G., Choi, J.J., Outten, C.A., Spencer, T.A., 1988, Intense electron beam cyclotron masers with microsecond pulse lengths. Conf. Digest 13th Int. Conf. on Infrared and Millimeter Waves, Honolulu, Hawaii, Proc., SPIE **1039**, 362-363.
- [311] Gilgenbach, R.M., Hochman, J.M., Jaynes, R., Walter, M.T., Rintamaki, J., Lash, J.S., Luginsland, J., Lau, Y.Y., Spencer, T.A., 1995, Rectangular interaction structures in high power gyrotron devices. Conf. Digest 20th Int. Conf. on Infrared and Millimeter Waves, Lake Buena Vista (Orlando), Florida, 528-529.
- [312] Hochman, J.M., Gilgenbach, R.M., Jaynes, R.L., Rintamaki, J.I., Lau, Y.Y., Spencer, T.A., 1997, High power microwave emission of large and small orbit rectangular cross section gyrotrons. Conf. Digest 22nd Int. Conf. on Infrared and Millimeter Waves, Wintergreen, Virginia, USA, pp. 315-316.
- [313] Hochman, J.M., Gilgenbach, R.M., Jaynes, R.L., Rintamaki, J.I., Lau, Y.Y., Cohen, W.E., Peters, C.W., Spencer, T.A., 1998, Polarization control of microwave emission from high power rectangular cross-section gyrotron devices. *IEEE Trans. on Plasma Science*, **PS-26**, 383-392.
- [314] Jaynes, R.L., Gilgenbach, R.M., Cohen, W.E., Lopez, M.R., Peters, C.W., Hochman, J.M., Lau, J.J., Spencer, T.A., 1999, High power microwave production in a coaxial, large orbit, axis encircling gyrotron oscillator. Conf. Digest 24<sup>th</sup> Int. Conf. on Infrared and Millimeter Waves, Monterey, California, USA, TU-A4.
- [315] Jaynes, R.L., Gilgenbach, R.M., Peters, C.W., Cohen, W.E., Lopez, M.R., Lau, Y.Y., Williams, W.J., Spencer, T.A., 2000, Long-pulse, high-power, large-orbit, coaxial gyrotron oscillator experiments. *IEEE Trans. on Plasma Science*, **PS 28**, 945-952.
- [316] Gilgenbach, R.M., Jaynes, R.L., Cohen, W.E., Peters, C.W., Lopez, M.R., Lau, Y.Y., Williams, W.J., Spencer, T.A., 2000, Experiments on slotted, coaxial, high power gyrotrons. Conf. Dig. Intense Microwave Pulses VII., Orlando, Florida, USA, SPIE-4031, 8-18.
- [317] Granatstein, V.L., Herndon, M., Sprangle, P., Carmel, Y., Nation, J.A., 1975, Gigawatt microwave emission from an intense relativistic electron beam. *Plasma Physics*, **17**, 23-28.
- [318] Gold, S.H., Fliflet, A.W., Manheimer, W.M., McCowan, R.B., Black, W.M., Lee, R.C., Granatstein, V.L., Kinkead, A.K., Hardesty, D.L., Sucey, M., 1987, High peak power Ka-band gyrotron oscillator experiment. *Phys. Fluids*, **30**, 2226-2238.

- [319] Gold, S.H., Fliflet, A.W., Manheimer, W.M., McCowan, R.B., Lee, R.C., Granatstein, V.L., Hardesty, D.L., Kinkead, A.K., Sucey, M., 1988, High peak power Ka-band gyrotron oscillator experiments with slotted and unslotted cavities. *IEEE. Trans. Plasma Science*, **PS-16**, 142, and, Gold, S.H., 1998, private communication.
- [320] Black, W.M., Gold, S.H., Fliflet, A.W., Kirkpatrick, D.A., Manheimer, W.M., Lee, R.C., Granatstein, V.L., Hardesty, D.L., Kinkead, A.K., Sucey, M., 1990, Megavolt Multikiloamp Ka-band gyrotron oscillator experiment. *Phys. Fluids*, **B2**, 193.
- [321] Didenko, A.N., Zherlitsyn, A.G., Zelentsov, V.I., Sulakshin, A.S., Fomenko, G.P., Shtein, Yu.G., Yushkov, Yu.G., 1976, Generation of gigawatt microwave pulses in the nanosecond range. *Sov. J. Plasma Phys.*, **2**, 283-285.
- [322] Cross, A.W., Spark, S.N., Phelps, A.D.R., 1988, Gyrotron experiments using cavities of different ohmic Q. *Conf. Digest 17th Int. Conf. on Infrared and Millimeter Waves, Pasadena, Proc., SPIE* **1929**, 392-393.
- [323] Cross, A.W., Spark, S.N., Phelps, A.D.R., 1995, Gyrotron experiments using cavities of different ohmic Q. *Int. J. Electronics*, **79**, 481-493.
- [324] Cross, A.W., MacGregor, S.J., Phelps, A.D.R., Ronald, K., Spark, S.N., Turnbull, S.M., 1995, Megawatt, 1 kHz PRF tunable gyrotron experiments. *Conf. Digest 20th Int. Conf. on Infrared and Millimeter Waves, Lake Buena Vista (Orlando), Florida*, 530-531.
- [325] Ronald, K., Cross, A.W., Phelps, A.D.R., He, W., 2001, Observations of dynamic behaviour in an electron cyclotron maser oscillator. *Appl. Phys.*, **34**, L17-L22.  
Ronald, K., Phelps, A.D.R., Cross, A.W., He, W., 2001, Observations of non-stationary behaviour in electron cyclotron masers. *Proc. 9th Int. Conf. Displays and Vacuum Electronics, Garmisch-Partenkirchen, ITG-Fachbericht 165*, pp. 159-162.
- [326] Bratman, V.L., Kalynov, Yu.K., Kolganov, N.G., Manuilov, V.N., Ofitserov, M.M., Savilov, A.V., Samsonov, S.V., Volkov, A.B., 1996, Cyclotron autoresonance masers and relativistic gyrotrons. *Proc. 3rd Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod, 1997, Vol.2*, pp. 745-761.
- [327] Bratman, V.L., Kalynov, Yu.K., Ofitserov, M.M., Samsonov, S.V., Savilov, A.V., 1997, CARMs and relativistic gyrotrons as effective sources and millimeter and submillimeter waves. *Conf. Digest 22nd Int. Conf. on Infrared and Millimeter Waves, Wintergreen, Virginia, USA*, pp. 58-60.
- [328] Bratman, V.L., Fedotov, A.E., Kalynov, Yu.K., Manuilov, V.N., Ofitserov, M.M., Samsonov, S.V., Savilov, A.V., 1998, Gyrotron on the 5th cyclotron harmonic. *Conf. Digest 23rd Int. Conf. on Infrared and Millimeter Waves, Colchester, UK*, pp. 325-326.
- [329] Bratman, V.L., Fedotov, A.E., Kalynov, Y.K., Manuilov, V.N., Ofitserov, M.M., Samsonov, V., Savilov, A.V., 1999, Moderately relativistic high-harmonic gyrotrons for millimeter/submillimeter wavelength band. *IEEE Trans. on Plasma Science*, **PS-27**, 456-461, and private communications.
- [330] Hogge, J.P., Cao, H., Kasperek, W., Tran, T.M., Tran, M.Q., Paris, P.J., 1991, Ellipsoidal diffraction grating as output coupler for quasi-optical gyrotrons. *Conf. Digest 16th Int. Conf. on Infrared and Millimeter Waves, Lausanne, Proc., SPIE* **1576**, 540-541.
- [331] Vlasov, S.N., Kuposova, E.V., Pavelyev, A.B., Khizhnyak, V.I. 1996, Gyrotrons with echelette resonators. *Radiophys. and Quantum Electronics*, **39**, 458-462.
- [332] Hu, W., Shapiro, M.A., Kreisler, K.E., Temkin, R.J., 1997, 140 GHz confocal cavity gyrotron experiment. *Conf. Digest 22nd Int. Conf. on Infrared and Millimeter Waves, Wintergreen, Virginia, USA*, pp. 116-117.
- [333] Hu, W., Shapiro, M.A., Kreisler, K.E., Temkin, R.J., 1998, 140-GHz gyrotron experiments based on a confocal cavity. *IEEE Trans. on Plasma Science*, **PS-26**, 366-374.
- [334] Gapochka, M.G., Korolev, A.F., Kostienko, A.I., Sukhorukov, A.P., Sheludchenkov, A.V., Golenitski, I.I., Evtushenko, O.V., Pulino, A., 1996, Compact low-voltage quasioptical millimeter-wave generators. *Proc. 25th European Microwave Conference, Prague*, 144-145.
- [335] Fliflet, A.W., Hargreaves, T.A., Fischer, R.P., Manheimer, W.M., Sprangle, P., 1990, Review of quasi-optical gyrotron development. *J. Fusion Energy*, **9**, 31-58.

- [336] Fischer, R.P., Fliflet, A.W., Manheimer, W.M., Levush, B., Antonsen Jr., T.M., 1993, Mode priming an 85 GHz quasioptical gyrokylystron. Conf. Digest 18th Int. Conf. on Infrared and Millimeter Waves, Colchester (Essex, UK), Proc., SPIE **2104**, 330-331.
- [337] Bratman, V.L., Denisov, G.G., 1992, Cyclotron autoresonance masers - recent experiments and prospects. Int. J. Electronics, **72**, 969-981.
- [338] Bratman, V.L., Denisov, G.G., Ofitserov, M.M., Samsonov, S.V., Arkhipov, O.V., Kazacha, V.I., Krasnykh, A.K., Perelstein, E.A., Zamrij, A.V., 1992, Cyclotron autoresonance maser with high Doppler frequency up-conversion. Int. J. Infrared and Millimeter Waves, **13**, 1857-1873.
- [339] Bratman, V.L., Denisov, G.G., Samsonov, S.V., 1993, Cyclotron autoresonance masers: achievements and prospects of advance to the submillimeter wavelength range. Proc. 2nd Int. Workshop on Strong Microwaves in Plasmas, Moscow - Nizhny Novgorod -Moscow, Inst. of Applied Physics, Nizhny Novgorod, 1994, Vol. 2, 690-711.
- [340] Bratman, V.L., Denisov, G.G., Kol'chugin, B.D., Samsonov, S.V., Volkov, A.B., 1995, Experimental demonstration of high-efficiency cyclotron-autoresonance-maser operation. Phys. Rev. Lett., **75**, 3102-3105.
- [341] Ginzburg, N.S., Zotova, I.V., Sergeev, A.S., Konoplev, I.V., 1997, Experimental observation of cyclotron superradiance under group synchronism conditions. Phys. Rev. Letters, **78**, 2365-2368.
- [342] Ginzburg, N.S., Zotova, I.V., Sergeev, A.S., Phelps, A.D.R., Cross, A.W., Shapk, V.G., Yaladin, M.I., Tarakanov, V.P., 1999, Generation of ultrashort microwave pulses based on cyclotron superradiance. IEEE Trans. on Plasma Science, **PS-27**, 462-469.
- [343] Bratman, V.L., Denisov, G.G., Kalynov, Yu.K., Samsonov, S.V., Savilov, A.V., Cross, A.W., He, W., Phelps, A.D.R., Ronald, K., Whyte, C.G., Young, A.R., 1999, Novel types of cyclotron resonance devices. Proc. 4<sup>th</sup> Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod, ed. A.G. Litvak, Inst. of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 2000, **Vol. 2**, pp. 683-702.
- [344] Bratman, V.L., Fedotov, A.E., Kolganov, N.G., Samsonov, S.V., Savilov, A.V., 2000, Effective co-generation of opposite and forward waves in cyclotron-resonance masers, Phys. Rev. Lett., **85**, 3424-3427.
- [345] Bratman, V.L., Fedotov, A.E., Savilov, A.V., 2000, A gyrodevice based on simultaneous excitation of opposite and forward waves (Gyrotron BWO-TWT). IEEE Trans. on Plasma Science, **PS-28**, 1742-1746.
- [346] Bratman, V.L., Fedotov, A.E., Kolganov, N.G., Samsonov, S.V., Savilov, A.V., 2001, Experimental study of CRM with simultaneous excitation of traveling and near-cutoff waves (CARM-Gyrotron). IEEE Trans. on Plasma Science, **PS-29**, 609-612.
- [347] Caplan, M., Kulke, B., Westenskow, G.A.; McDermott, D.B., Luhmann, Jr., N.C., 1992, Induction-linac-driven, millimeter-wave CARM oscillator. Laboratory Report UCRL-53689-80, Lawrence Livermore National Laboratory, Livermore, California.
- [348] Danly, B.G., Hartemann, F.V., Chu, T.S., Legorburn, P., Menninger, W.L, Temkin, R.J., 1992, Long-pulse millimeter-wave free-electron laser and cyclotron autoresonance maser experiments. Phys. Fluids, **B4**, 2307-2314.
- [349] Alberti, S., Danly, B.G., Gulotta, G., Giguette, E., Kimura, T., Menninger, W.L., Rullier, J.L., Temkin, R.J., 1993, Experimental study of a 28 GHz high-power long-pulse cyclotron autoresonance maser oscillator. Phys. Rev. Lett., **71**, 2018-2021.
- [350] Wang, J.G., Gilgenbach, R.M., Choi, J.J., Outten, C.A., Spencer, T.A., 1989, Frequency-tunable, high-power microwave emission from cyclotron autoresonance maser oscillation and gyrotron interactions. IEEE Trans. Plasma Science, **17**, 906-908.
- [351] Choi, J.J., Gilgenbach, R.M., Spencer, T.A., 1992, Mode competition in Bragg resonator cyclotron resonance maser experiments driven by a microsecond intense electron beam. Int. J. Electronics, **72**, 1045-1066.

- [352] Cooke, S.J., Cross, A.W., He, W., Phelps, A.D.R., 1995, The operation of a second harmonic CARM oscillator. Conf. Digest 20th Int. Conf. on Infrared and Millimeter Waves, Lake Buena Vista (Orlando), Florida, 427-428.
- [353] Cooke, S.J., Cross, A.W., He, W., Phelps, A.D.R., 1996, Experimental operation of a cyclotron autoresonance maser oscillator at the second harmonic. Phys. Rev. Lett., **77**, 4836-4839.
- [354] Young, A.R., He, W. Ronald, K., Cross, A.W., Whyte, C.G., Phelps, A.D.R., 1998, Cold and thermionic cathode CARM experiments. Conf. Digest 23rd Int. Conf. on Infrared and Millimeter Waves, Colchester, UK, pp. 448-449.
- [355] Felch, K., James, B.G., Borchard, P., Cahalan, P., Chu, T.S., Hargreaves, T.A., Blank, M., Pershing, D.E., Calame, J.P., Nguyen, K., Danly, B.G., Levush, B., 1999, Recent test results for a 10 kW average power W-band gyrokystron amplifier. Conf. Digest 24<sup>th</sup> Int. Conf. on Infrared and Millimeter Waves, Monterey, California, USA, M-A5.
- [356] Blank, M., Danly, G., Levush, B., Calame, J.P., Nguyen, K., Pershing, D., Petillo, J., Hargreaves, T.A., True, R.B., Theiss, J., Good, G.R., Felch, K., James, B.G., Borchard, P., Cahalan, P., Chu, T.S., Jory, H., Lawson, W.G., Antonsen, Jr., T.M., 1999, Demonstration of a 10 kW average power 94 GHz gyrokystron amplifier. Phys. of Plasmas, **6**, 4405-4409.
- [357] Blank, M., Felch, K., James, B.G., Borchard, P., Cahalan, P., Chu, T.S., Jory, H., Hargreaves, T.A., True, R.B., Theiss, A.J., Good, G.R., Danly, B.G., Levush, B., Calame, J.P., Nguyen, K., Pershing, D., Petillo, J., Lawson, W.G., Antonsen, T.M. jr., 1999, Experimental demonstration of a high-average power W-band gyrokystron amplifier. Proc. 4<sup>th</sup> Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod, ed. A.G. Litvak, Inst. of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 2000, **Vol. 2**, pp. 703-712.
- [358] Blank, M., Felch, K., James, B.G., Borchard, P., Cahalan, P., Chu, T.S., Danly, B.G., Pershing, D.E., Nguyen, K., Calame, J.P., Levush, B., 2000, Demonstration of high average power W-band gyro-amplifiers. Conf. Digest 25th Int. Conf. on Infrared and Millimeter Waves, Beijing, P.R. China, pp. 113-114.
- [359] Blank, M., Danly, B.G., Levush, B., 2000, Experimental demonstration of W-band gyrokystron amplifiers with improved gain and efficiency. IEEE Trans. on Plasma Science, **PS-28**, 706-711.
- [360] Danly, B.G., Blank, M., Calame, J.P., Levush, B., Nguyen, K.T., Pershing, D.E., Parker, R.K., Felch, K.L., James, B.G., Borchard, P., Cahalan, P., Chu, T.S., Jory, H.R., Hargreaves, T.A., True, R.B., Lawson, W.G., Antonsen, T.M., 2000, Development and testing of a high-average power, 94-GHz gyrokystron. IEEE Trans. on Plasma Science, **PS-28**, 713-726.
- [361] Antakov, I.I., Zasytkin, E.V., Sokolov, E.V., Yulpatov, V.K., Keyer, A.P., Musatov, V.S., Myasnikov, V.E., 1993, 35 GHz radar gyrokystrons. Conf. Digest 18th Int. Conf. on Infrared and Millimeter Waves, Colchester (Essex, UK), Proc., SPIE **2104**, 338-339.
- [362] Antakov, I.I., Gaponov, A.V., Zasytkin, E.V., Sokolov, E.V., Yulpatov, V.K., Aksenova, L.A., Keyer, A.P., Musatov, V.S., Myasnikov, V.E., Popov, L.G., Levitan, B.A., Tolkachev, A.A., 1993, Gyrokystrons: millimeter wave amplifiers of the highest power. Proc. 2nd Int. Workshop on Strong Microwaves in Plasmas, Moscow - Nizhny Novgorod - Moscow, ed. A.G. Litvak, Inst. of Applied Physics, Nizhny Novgorod, 1994, **Vol. 2**, 587-596.
- [363] Antakov, I.I., Aksenova, L.A., Zasytkin, E.V., Moiseev, M.A., Popov, L.G., Sokolov, E.V., Yulpatov, V.K., 1990, Multicavity phase-locked gyrotrons for lower-hybrid heating in toroidal plasmas. Proc. Int. Workshop on Strong Microwaves in Plasmas, Suzdal, Inst. of Applied Physics, Nizhny Novgorod, 1991, 773-782.
- [364] Antakov, I.I., Moiseev, M.A., Sokolov, E.V., Zasytkin, E.V., 1993, Theoretical and experimental investigation of X-band two-cavity gyrokystron. Conf. Digest 18th Int. Conf. on Infrared and Millimeter Waves, Colchester (Essex, UK), Proc., SPIE **2104**, 336-337.

- [365] Antakov, I.I., Moiseev, M.A., Sokolov, E.V., Zasytkin, E.V., 1994, Theoretical and experimental investigation of X-band two-cavity gyrokystron. *Int. J. of Infrared and Millimeter Waves*, **15**, 873-887.
- [366] Zasytkin, E.V., Moiseev, M.A., Sokolov, E.V., Yulpatov, V.K., 1995, Effect of penultimate cavity position and tuning on three-cavity gyrokystron amplifier performance. *Int. J. Electronics*, **78**, 423-433.
- [367] Zasytkin, E.V., Moiseev, M.A., Gachev, I.G., Antakov, I.I., 1996, Study of high-power Ka-band second-harmonic gyrokystron amplifier. *IEEE Trans. on Plasma Science*, **PS-24**, 666-670.
- [368] Antakov, I.I., Gachev, I.G., Sokolov, E.V., 1995, Experimental study of two-cavity gyrotron with feedback between cavities. *Proc. Conf.: Intense Microwave-Pulses III*, San Diego, *Proc. SPIE* **2557**, 380-385.
- [369] Antakov, I.I., Zasytkin, E.V., Sokolov, E.V., 1993, Design and performance of 94 GHz high power multicavity gyrokystron amplifier. *Conf. Digest 18th Int. Conf. on Infrared and Millimeter Waves*, Colchester (Essex, UK), *Proc.*, *SPIE* **2104**, 466-467 and *Proc. 2nd Int. Workshop on Strong Microwaves in Plasmas*, Moscow - Nizhny Novgorod - Moscow, ed. A.G. Litvak, *Inst. of Applied Physics, Nizhny Novgorod*, 1994, **Vol. 2**, 754-758.
- [370] Zasytkin, E.V., Gachev, I.G., Antakov, I.I., Moiseev, M.A., Lygin, V.K., Sokolov, E.V., 1998, Development of a W-band 120 kW gyrokystron at IAP. *Conf. Digest 23rd Int. Conf. on Infrared and Millimeter Waves*, Colchester, UK, p. 183.
- [371] Zasytkin, E.V., Gachev, I.G., Antakov, I.I., Moiseev, M.A., Zavolsky, N.A., 1999, Study of a W-band pulsed 200 kW gyrokystron amplifier. *Conf. Digest 24<sup>th</sup> Int. Conf. on Infrared and Millimeter Waves*, Monterey, California, USA, W-A2.
- [372] Gachev, I.G., Antakov, I.I., Moiseev, M.A., Sokolov, E.V., Zavolsky, N.A., Zasytkin, E.V., 1999, 200 kW pulsed W-band gyrokystron amplifier. *Proc. 4<sup>th</sup> Int. Workshop on Strong Microwaves in Plasmas*, Nizhny Novgorod, ed. A.G. Litvak, *Inst. of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod*, 2000, **Vol. 2**, pp. 713-717.
- [373] Gachev, I.G., Antakov, I.I., Zasytkin, E.V., 2000, Status of a W-band pulsed 200 kW gyrokystron experiment. *Conf. Digest 25th Int. Conf. on Infrared and Millimeter Waves*, Beijing, P.R. China, pp. 181-182.
- [374] Zasytkin, E.V., Gachev, I.G., Antakov, I.I., Sokolov, E.V., 2001, W-band pulsed 300 kW gyrokystron amplifier. *Conf. Digest, 26th Int. Conf. on Infrared and Millimeter Waves*, Toulouse, France.
- [375] Choi, J.J., McCurdy, A.H., Wood, F., Kyser, Calame, J., Nguyen, K., Danly, B.G., Levush, B., Parker, R.K., 1997, High power 35 GHz gyrokystron amplifiers. *Conf. Digest 22nd Int. Conf. on Infrared and Millimeter Waves*, Wintergreen, Virginia, USA, pp. 229-230.
- [376] Choi, J.J., McCurdy, A.H., Wood, F.N., Kyser, R.H., Calame, J.P., Nguyen, K.T., Danly, B.G., Antonsen, T.M., Levush, B., Parker, R.K., 1998, Experimental investigation of a high power, two-cavity, 35 GHz gyrokystron amplifier. *IEEE Trans. on Plasma Science*, **PS-26**, 416-425.
- [377] Garven, M., Calame, J.P., Choi, J.J., Danly, B.G., Nguyen, K.T., Wood, F., 1998, Experimental 35 GHz multi-cavity gyrokystron amplifiers. *Conf. Digest 23rd Int. Conf. on Infrared and Millimeter Waves*, Colchester, UK, pp. 28-29.
- [378] Garven, M., Calame, J.P., Danly, B.G., Levush, B., Nguyen, K.T., Wood, F.N., 1999, Experimental studies of a high gain 35 GHz gyrokystron amplifier. *Conf. Digest 24<sup>th</sup> Int. Conf. on Infrared and Millimeter Waves*, Monterey, California, USA, M-A6.
- [379] Calame, J.P., Garven, M., Choi, J.J., Nguyen, K., Wood, F., Blank, M., Danly, B.G., Levush, B., 1999, Experimental studies of bandwidth and power production in a three-cavity 35 GHz gyrokystron amplifier. *Phys. of Plasmas*, **6**, 285-297.
- [380] Garven, M., Calame, J.P., Nguyen, K.T., Danly, B.G., Levush, B., Wood, F.N., 2000, Experimental studies of a four-cavity, 35 GHz gyrokystron amplifier. *IEEE Trans. on Plasma Science*, **PS-28**, 672-680.



- [381] Blank, M., Danly, B.G., Levush, B., Latham, P.E., Pershing, D.E., 1997, Experimental demonstration of a W-band gyrokystron amplifier, *Phys. Rev. Lett.*, **79**, 4485-4488.
- [382] Blank, M., Danly, B.G., Levush, B., Pershing, D.E., 1998, Experimental investigation of W-band (93 GHz) gyrokystron amplifiers. *IEEE Trans. on Plasma Science*, **PS-26**, 409-415.
- [383] Blank, M., Danly, B.G., Levush, B., 1998, Experimental demonstration of W-band gyro-amplifiers with improved performance. *Conf. Digest 23rd Int. Conf. on Infrared and Millimeter Waves*, Colchester, UK, pp. 26-27.
- [384] Danly, B.G., Blank, M., Calame, J.P., Levush, B., Nguyen, K., Pershing, D., Petillo, J., Hargreaves, T.A., True, R.B., Theiss, A.J., Good, G.R., Felch, K., Chu, T.S., Jory, H., Borchard, P., James, B.G., Lawson, W.G., Antonsen, T.M., 1998, Development of a W-band gyrokystron for radar applications. *Conf. Digest 23rd Int. Conf. on Infrared and Millimeter Waves*, Colchester, UK, pp. 32-33.
- [385] Burke, J.M., Czarnaski, M.A., Fischer, R.P., Giangrave, M., Fliflet, A.W., Manheimer, W.M., 1991, 85 GHz TE<sub>13</sub> phase-locked gyrokystron oscillator experiment. *Conf. Digest 13th Int. Conf. on Infrared and Millimeter Waves*, Honolulu, Hawaii, Proc., SPIE **1039**, 228-229.
- [386] Fischer, R.P., Fliflet, A.W., Manheimer, W.M., 1992, The NRL 85 GHz quasi-optical gyrokystron experiment. *Conf. Digest 17th Int. Conf. on Infrared and Millimeter Waves*, Pasadena, Proc., SPIE **1039**, 254-255.
- [387] Tantawi, S.G., Main, W.T., Latham, P.E., Nusinovich, G.S., Lawson, W.G., Striffler, C.D., Granatstein, V.L., 1992, High-power X-band amplification from an overmoded three-cavity gyrokystron with a tunable penultimate cavity. *IEEE Trans. Plasma Science*, **PS-20**, 205-215.
- [388] Lawson, W., Calame, J.P., Hogan, P., Skopec, M., Striffler, C.D., Granatstein, V.L., 1992, Performance characteristics of a high-power X-band two-cavity gyrokystron. *IEEE Trans. Plasma Science*, **PS-20**, 216-223.
- [389] Matthews, H.W., Lawson, W., Calame, J.P., Flaherty, M.K.E., Hogan, B., Cheng, J., Latham, P.E., 1994, Experimental studies of stability and amplification in a two-cavity second harmonic gyrokystron. *IEEE Trans. Plasma Science*, **PS-22**, 825-833.
- [390] Lawson, W., Hogan, B., Calame, J.P., Cheng, J., Latham, P.E., Granatstein, V.L., 1994, Experimental studies of 30 MW fundamental mode and harmonic gyro-amplifiers. *Conf. Digest 19th Int. Conf. on Infrared and Millimeter Waves*, Sendai, JSAP Catalog No.: AP 941228, 421-422.
- [391] Park, G.-S., Granatstein, V.L., Park, S.Y., Armstrong, C.M., Ganguly, A.K., 1992, Experimental study of efficiency optimization in a three-cavity gyrokystron amplifier. *IEEE Trans. on Plasma Science*, **PS-20**, 224-231.
- [392] Lawson, W., Hogan, B., Flaherty, M.K.E., Metz, H., 1996, Design and operation of a two-cavity third harmonic Ka-band gyrokystron, *Appl. Phys. Lett.*, **63**, 1849-1851.
- [393] Lawson, W., Cheng, J., Calame, J.P., Castle, M., Hogan, B., Granatstein, V.L., Reiser, M., Saraph, G.P., 1998, High power operation of a three-cavity X-band coaxial gyrokystron, *Phys. Rev. Lett.*, **81**, 3030-3033.
- [394] Lawson, W., Cheng, J., Hogan, B., Granatstein, V.L., Xu, X., 1998, High power operation of an 8.6 GHz coaxial gyrokystron. *Conf. Digest 23rd Int. Conf. on Infrared and Millimeter Waves*, Colchester, UK, pp. 373-374.
- [395] Cheng, J., Xu, X., Lawson, J., Calame, J.P., Castle, M., Hogan, B.P., Granatstein, V.L., Nusinovich, G.S., Reiser, M., 1999, Experimental studies of a high-power, x-band, coaxial gyrokystron. *IEEE Trans. on Plasma Science*, **PS-27**, 1175-1187.
- [396] Ferguson, E., Symons, R.S., 1981, A gyro-TWT with a space-charged limited gun. *Proc. Int. Electron Device Meeting*, 198-201.
- [397] Eckstein, J.N., Latshaw, D.W., Stone, D.S., 1983, 95 GHz gyro traveling wave tube, VARIAN Assoc., Final Rep. Contract DASG60-79-C-005 MOD P003 (BMDACTC), and Bohlen, H.P., Felch, K., 1996, private communication, CPI, Palo Alto.

- [398] Bratman, V.L., Cross, A.W., Denisov, G.G., He, W., Phelps, A.D.R., Ronald, K., Samsonov, S.V., Whyte, C.G., Young, A.R., 2000, Efficient wide-band gyro-TWT with a helically grooved waveguide, Conf. Digest 25th Int. Conf. on Infrared and Millimeter Waves, Beijing, P.R. China, pp. 175-176.
- [399] Denisov, G.G., 2001, Development of frequency-tunable high-power gyro-devices. Conf. Digest, 26th Int. Conf. on Infrared and Millimeter Waves, Toulouse, France.
- [400] Park, G.S., Park, S.Y., Kyser, R.H., Armstrong, C.M., Ganguly, A.K., Parker, R.K., 1994, Broadband operation of a Ka-band tapered gyro-traveling wave amplifier. IEEE Trans. Plasma Science, **PS-22**, 536-543.
- [401] Park, G.S., Choi, J.J., Park, S.J., Armstrong, C.M., Ganguly, A.K., Kyser, R.H., Parker, R.K., 1995, Gain broadening of two-stage tapered gyrotron traveling wave tube amplifier, Phys.Rev.Lett., **74**, 2399-2402.
- [402] Choi, J.J., Park, G.S., Ganguly, A.K., Armstrong, C.M., Calise, F., Wood, F., Sobocinski, B., Parker, R.K., 1995, Experimental investigation on broadband millimeter wave gyro-TWT amplifiers. Conf. Digest 20th Int. Conf. on Infrared and Millimeter Waves, Lake Buena Vista (Orlando), Florida, 343-344.
- [403] Leou, K.C., McDermott, D.B., Luhmann, Jr., N.C., 1992, Design of experimental dielectric loaded wideband Gyro-TWT. Conf. Digest 17th Conf. on Infrared and Millimeter Waves, Pasadena, Proc., SPIE **1929**, 326-327.
- [404] Leou, K.C., Wang, Q.S., Chong, C.K., Balkcum, A.J., Fochs, S.N., Garland, E.S., Pretterebner, J., Lin, A.T., McDermott, D.B., Hartemann, F., Luhmann, Jr., N.C., 1993, Gyro-TWT amplifiers at UCLA, Conf. Digest 18th Int. Conf. on Infrared and Millimeter Waves, Colchester (Essex, UK), Proc., SPIE **2104**, 531-532.
- [405] Wang, Q.S., Leou, K.C., Chong, C.K., Balkeum, A.J., McDermott, D.B., Luhmann, Jr., N.C., 1994, Gyro-TWT amplifier development at UCD. Conf. Digest 19th Int. Conf. on Infrared and Millimeter Waves, Sendai, JSAP Catalog No.: AP 941228, 415-416.
- [406] Wang, Q.S., McDermott, D.B. Luhmann, Jr., N.C., 1995, Stable operation of a 200 kW second harmonic TE<sub>21</sub> gyro-TWT amplifier. Conf. Digest 20th Int. Conf. on Infrared and Millimeter Waves, Lake Buena Vista (Orlando), Florida, 347-348.
- [407] Wang, Q.S., McDermott, D.B. Luhmann, Jr., N.C., 1995, Demonstration of marginal stability by a 200 kW second-harmonic gyro-TWT amplifier. Phys. Rev. Lett. **75**, 4322-4325.
- [408] Wang, Q.S., McDermott, D.B., Luhmann, Jr., N.C., 1996, Operation of a stable 200-kW second-harmonic gyro-TWT amplifier. IEEE Trans. on Plasma Science, **PS-24**, 700-706.
- [409] Leou, K.C., McDermott, D.B., Luhmann, Jr., N.C., 1996, Large-signal characteristics of a wide-band dielectric-loaded gyro-TWT amplifier. IEEE Trans. on Plasma Science, **PS-24**, 718-726.
- [410] Furano, D.S., McDermott, D.B., Kou, C.S., Luhman, Jr., N.C., Vitello, P., 1989, Theoretical and experimental investigation of a high-harmonic gyro-TWT amplifier. Phys. Rev. Lett., **62**, 1314-1317.
- [411] Chong, C.K., McDermott, D.B., Luhmann, Jr., N.C., 1998, Large-signal operation of a third-harmonic slotted gyro-TWT amplifier. IEEE Trans. on Plasma Science, **PS-26**, 500-507.
- [412] Chu, K.R., Barnett, L.R., Lau, W.K., Chang, L.H., Chen H.Y., 1990, A wide-band millimeter-wave gyrotron traveling-wave amplifier experiment. IEEE Trans. Electron. Devices, **ED-37**, 1557-1560.
- [413] Chu, K.R., Barnett, L.R., Chen, H.Y., Chen, S.H., Wang, CH., Yeh, Y.S., Tsai, Y.C., Yang, T.T., Dawn, T.Y., 1995, Stabilization of absolute instabilities in the gyrotron traveling wave amplifier. Phys. Rev. Lett., **74**, 1103-1106 and, 1997, private communication.
- [414] Chu, K.R., Chen, H.Y., Hung, C.L., Chang, T.H., Barnett, L.R., Chen, S.H., Yang, T.T., An ultra high gain gyrotron travelling wave amplifier. 1998, Conf. Digest 23rd Int. Conf. on Infrared and Millimeter Waves, Colchester, UK, pp. 30-31.

- [415] Chu, K.R., Chen, H.Y., Hung, C.L., Chang, T.H., Barnett, L.R., Chen, S.H., Yang, T.T., 1998, Ultrahigh gain gyrotron travelling wave amplifier. *Phys. Rev. Lett.*, **81**, 4760-4763.
- [416] Chu, K.R., Chang, T.H., Chen, H.Y., Hung, C.L., Barnett, L.R., Chen, S.H., Yang, T.T., 1999, Physics and technology issues of the gyrotron traveling wave amplifier. *Proc. 4<sup>th</sup> Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod*, ed. A.G. Litvak, Inst. of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 2000, **Vol. 2**, pp. 718-727.
- [417] Denisov, G.G., Bratman, V.L., Cross, A.W., He, W., Phelps, A.D.R., Ronald, K., Samsonov, S.V., Whyte, C.G., 1998, Experimental results from a helical waveguide gyro-TWT. *Conf. Digest 23rd Int. Conf. on Infrared and Millimeter Waves, Colchester, UK*, pp. 170-172.
- [418] Denisov, G.G., Bratman, V.L., Cross, A.W., He, W., Phelps, A.D.R., Ronald, K., Samsonov, S.V., Whyte, C.G., 1998, Gyrotron traveling wave amplifier with a helical interaction waveguide. *Phys. Rev. Letters*, **81**, 5680-5683.
- [419] Bratman, V.L., Cross, A.W., Denisov, G.G., He, W., Phelps, A.D.R., Ronald, K., Samsonov, S.V., Whyte, C.G., Young, A.R., 1999, Frequency-broadband gyro-travelling wave amplifier operating with eigenwaves of helically rippled waveguides. *Conf. Digest 24<sup>th</sup> Int. Conf. on Infrared and Millimeter Waves, Monterey, California, USA, M-4A*, and private communication.
- [420] Bratman, V.L., Cross, A.W., Denisov, G.G., He, W., Phelps, A.D.R., Ronald, K., Samsonov, S.V., Whyte, C.G., Young, A.R., 2000, High-gain wide-band gyrotron travelling wave amplifier with a helically corrugated waveguide. *Phys. Rev. Lett.*, **84**, 2746-2749.
- [421] Phelps, A.D.R., Bratman, V.L., Cross, A.W., Denisov, G.G., He, W., Ronald, K., Samsonov, S.V., Whyte, C.G., Young, A.R., 2001, A broadband, efficient, gyrotron amplifier. *Proc. 9th Int. Conf. Displays and Vacuum Electronics, Garmisch-Partenkirchen, ITG-Fachbericht 165*, pp. 193-198.
- [422] Menninger, W.L., Danly, B.G., Temkin, R.J., 1996, Multimegawatt relativistic harmonic gyrotron traveling-wave tube amplifier experiments. *IEEE Trans. on Plasma Science*, **PS-24**, 687-699.
- [423] Gold, S.H., Fliflet, A.W., Kirkpatrick, D.A., 1989, High-power millimeter-wave gyro-traveling-wave amplifier. *Conf. Digest 14th Int. Conf. on Infrared and Millimeter Waves, Würzburg, SPIE 1240*, 332-333.
- [424] Gold, S.H., Kirkpatrick, D.A., Fliflet, A.W., McCowan, R.B., Kinkaed, A.K., Hardesty, D.L., Sucey, M., 1991, High voltage millimeter-wave gyro-travelling-wave amplifier. *J. Appl. Phys.*, **69**, 6696-6698, and, Gold, S.H., 1998, private communication.
- [425] Blank, M., Danly, B.G., Levush, B., 1999, Experimental demonstration of a W-band (94 GHz) gyrotwystron amplifier. *IEEE Trans. on Plasma Science*, **PS-27**, 405-411.
- [426] Zasytkin, E.V., Levush, B., Blank, M., Sokolov, E.V., Antakov, I.I., 1997, Study of X-band three-stage gyrotwystron amplifier. *Conf. Digest 22nd Int. Conf. on Infrared and Millimeter Waves, Wintergreen, Virginia, USA*, pp. 281-282.
- [427] Blank, M., Zasytkin, E.V., Levush, B., 1998, An investigation of X-band gyrotwystron amplifiers. *IEEE Trans. on Plasma Science*, **PS-26**, 577-581.
- [428] Guo, H., Chen, S.-H., Granatstein, V.L., Rodgers, J., Nusinovich, G.S., Walter, M.T., Zhao, J., Chen, W., 1998, Operation of a high performance, harmonic-multiplying, inverted gyrotwystron. *IEEE Trans. on Plasma Science*, **PS-26**, 451-460.
- [429] Guo, H., Chen, S.H., Granatstein, V.L., Rodgers, J., Nusinovich, G., Walter, M., Levush, B., Chen, W.J., 1997, Operation of a highly overmoded, harmonic-multiplying gyrotron amplifier. *Phys. Rev. Lett.*, **79**, 515-518.
- [430] Rodgers, J., Guo, H., Granatstein, V.L., Chen, S.H., Nusinovich, G.S., Walter, M., Zhao, J., 1999, High efficiency, phase-locked operation of the harmonic-multiplying inverted gyrotwystron oscillator. *IEEE Trans. on Plasma Science*, **PS-27**, 412-421.

- [431] Guo, H., Rodgers, J., Zhao, J., Miao, Y.Y., Chen, W.J., Granatstein, V.L., 2000, Latest progress in studies of harmonic multiplying gyro-amplifiers, Conf. Digest 25th Int. Conf. on Infrared and Millimeter Waves, Beijing, P.R. China, pp. 317-318.
- [432] Lawson, W., Latham, P.E., Calame, J.P., Cheng, J., Hogan, B., Nusinovich, G.S., Irwin, V., Granatstein, V.L., Reiser, M., 1995, High power operation of first and second harmonic gyrotwistrons. *J. Appl. Phys.*, **78**, 550-559.
- [433] Basten, M.A., Guss, W.C., Kreischer, K.E., Temkin, R.T., Caplan, M., 1995, Experimental investigation of a 140 GHz gyrotron-backward wave oscillator. *Int. J. Infrared and Millimeter Waves*, **16**, 880-905.
- [434] Park, S.Y., Kyser, R.H., Armstrong, C.M., Parker, R.K., Granatstein, V.L., 1990, Experimental Study of a Ka-band gyrotron backward-wave oscillator. *IEEE Trans. on Plasma Science*, **PS-18**, 321-325.
- [435] Kou, C.S., Chen, S.H., Barnett, L.R., Chu, K.R., 1993, Experimental study of an injection locked gyrotron backward wave oscillator. *Phys. Rev. Lett.*, **70**, 924-927.
- [436] Chang, T.H., Chen, S.H., Cheng, F.H., Kou, C.S., Chu, K.R., 1999, Experimental study of an injection locked gyro-BWO. Conf. Digest 24<sup>th</sup> Int. Conf. on Infrared and Millimeter Waves, Monterey, California, USA, M-A2.
- [437] Chu, K.R., Chen, S.H., Chang, T.H., 2000, Review of the gyrotron backward wave oscillator. Conf. Digest 25th Int. Conf. on Infrared and Millimeter Waves, Beijing, P.R. China, pp. 9-10.
- [438] Schriever, R.L., Johnson, C.C., 1966, A rotating beam waveguide oscillator. *Proc. of the IEEE*, 2029-2030.
- [439] Bratman, V.L., Denisov, G.G., Phelps, A.D.R., Samsonov, S.V., 1998, Gyro-TWTs and gyro-BWOs with helical waveguides. Proc. Research Workshop of the Israel Science Foundation on Cyclotron Resonance Masers and Gyrotrons, 1998, Kibbutz Ma'ale Hachamisha, Israel, pp. 252-264.
- [440] Bratman, V.L., Fedotov, A.E., Savilov, A.V., 1999, A new type of gyro-BWO (gyro-BWT-TWT). Conf. Digest 24<sup>th</sup> Int. Conf. on Infrared and Millimeter Waves, Monterey, California, USA, TH-E6.
- [441] Kamada, K., Nawashiro, K., Tamagawa, F., Igarashi, H., Kizu, S., Lee, C.-Y., Kawasaki, S., Ando, R., Masuzaki, M., 1998, Backward wave oscillator experiments with a relativistic electron beam using an X-band rectangular waveguide. *Int. J. of Infrared and Millimeter Waves*, **19**, 1317-1324.
- [442] Kamada, K., Nawashiro, K., Tamagawa, F., Lee, C.-Y., Yoshida, H., Kawasaki, S., Ando, R., Masuzaki, M., 2000, Dependence of output power on cavity length in a gyrotron backward wave oscillator. *Int. J. of Infrared and Millimeter Waves*, **21**, 1441-1449.
- [443] Walter, M.T., Gilgenbach, R.M., Menge, P.R., Spencer, T.A., 1994, Effects of tapered tubes on long-pulse microwave emission from intense e-beam gyrotron-backward-wave oscillators. *IEEE Trans. Plasma Sciences*, **PS-22**, 578-584.
- [444] Walter, M.T., Gilgenbach, R.M., Luginsland, J.W., Hochman, J.M., Rintamaki, J.I., Jaynes, R.L., Lau, Y.Y., Spencer, T.A., 1996, Effects of tapering on gyrotron backward-wave oscillators. *IEEE Trans. on Plasma Science*, **PS-24**, 636-647.
- [445] Spencer, T.A., Arman, M.J., Hendricks, K.J., Hackett, K.E., Stump, M., Gilgenbach, R.M., 1995, Non-axisymmetric mode competition in a high current, high voltage TE<sub>01</sub> gyrotron-backward-wave oscillator experiment. Conf. Digest 20th Int. Conf. on Infrared and Millimeter Waves, Lake Buena Vista (Orlando), Florida, 536-537.
- [446] Spencer, T.A., Davis, C.E., Hendricks, K.J., Agee, F.J., Gilgenbach, R.M., 1996, Results from gyrotron backward wave oscillator experiments utilizing a high-current high-voltage annular electron beam. *IEEE Trans. on Plasma Science*, **PS-24**, 630-635.
- [447] Ono, S., Yamanouchi, K., Shibata, Y., Koike, Y., 1962, Cyclotron fast-wave tube using spatial harmonic interaction- the traveling wave peniotron. Proc. 4th Int. Congress Microwave Tubes, Scheveningen, 355-363.

- [448] Ono, S., Tsutaki, K., Kageyama, T., 1984, Proposal of a high efficiency tube for high power millimetre or submillimetre wave generation: The gyro-peniotron. *Int. J. Electronics*, **56**, 507-519.
- [449] Yokoo, K., Razeghi, M., Sato, N., Ono, S., 1988, High efficiency operation of the modified peniotron using TE<sub>11</sub> rectangular waveguide cavity. *Conf. Digest, 13th Int. Conf. on Infrared and Millimeter Waves, Honolulu, Hawaii, Proc., SPIE 1039*, 135-136
- [450] Yokoo, K., Musyoki, S., Nakazato, Y., Sato, N., Ono, S., 1990, Design and experiments of auto-resonant peniotron oscillator. *Conf. Digest 15th Int. Conf on Infrared and Millimeter Waves, Orlando, Proc., SPIE 1514*, 10-12.
- [451] Yokoo, K., Shimawaki, H., Tadano, H., Ishihara, T., Sagae, N., Sato, N., Ono, S., 1992, Design and experiments of higher cyclotron harmonic peniotron oscillators. *Conf. Digest 17th Int. Conf. on Infrared and Millimeter Waves, Pasadena, Proc., SPIE 1929*, 498-499.
- [452] Musyoki, S., Sagae, K., Yokoo, K., Sato, N., Ono, S., 1992, Experiments on highly efficient operation of the auto-resonant peniotron oscillator. *Int. J. Electronics*, **72**, 1067-1077.
- [453] Yokoo, K., Ishihara, T., Sagae, K., Shimawaki, H., Sato, N., 1997, Experiments of space harmonic peniotron for cyclotron high harmonic operation. *Conf. Digest 22nd Int. Conf. on Infrared and Millimeter Waves, Wintergreen, Virginia, USA*, pp. 206-207.
- [454] Yokoo, K., Ishihara, T., Sagae, K., Sato, N., Shimawaki, H., 1998, Efficient operation of high harmonic peniotron in millimeter wave region. *Proc. 8th ITG-Conference on Displays and Vacuum Electronics, Garmisch-Partenkirchen, ITG-Fachbericht 150*, pp. 447-452.
- [455] Ishihara, T., Sagae, K., Sato, N., Shimawaki, H., Yokoo, K., 1999, Highly efficient operation of space harmonic peniotron at cyclotron high harmonics. *IEEE Trans. on Electron Devices*, **ED-46**, 798-802.
- [456] Ono, S., Ansai, H., Sato, N., Yokoo, K., Henmi, K., Idehara, T., Tachikawa, T., Okazaki, I., Okamoto, T., 1986, Experimental study of the 3rd harmonic operation of gyro-peniotron at 70 GHz. *Conf. Digest 11th Int. Conf. on Infrared and Millimeter Waves, Pisa*, 37-39, and Okazaki, Y., 1994, private communication, Toshiba, Otawara, Japan.
- [457] Ostreiko, G.N., Kozyrev, E.V., Makarov, I.G., Nezhevenko, O.A., Persov, B.Z., Serdobintsev, G.V., Shchelkunoff, S.V., Tarnetsky, V.V., Yakolov, V.P., Zapryagaev, I.A., 1996, The results of 7 GHz pulse magnicon investigation. *Proc. 3rd Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod, 1997, Vol.2*, pp. 861-870.
- [458] Kozyrev, E.V., Nezhevenko, O.A., Nikiforov, A.A., Ostreiko, G.N., Persov, B.Z., Serdobintsev, G.V., Shchelkunoff, S.V., Tarnetsky, V.V., Yakolev, V.P., Zapryagaev, I.A., 1999, 7 GHz 55 MW pulsed magnicon. *Proc. 4th Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod, Russia*.
- [459] Kozyrev, E.V., Nezhevenko, O.A., Nikiforov, A.A., Ostreiko, G.N., Persov, B.Z., Serdobintsev, G.V., Shchelkunoff, S.V., Tarnetsky, V.V., Yakovlev, V.P., Zapryagaev, I.A., 1999, 7 GHz 55 MW pulsed magnicon. *Proc. 4<sup>th</sup> Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod*, ed. A.G. Litvak, Inst. of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 2000, **Vol. 2**, pp. 740-746.
- [460] Kozyrev, E.V., Nezhevenko, O.A., Nikiforov, A.A., Ostreiko, G.N., Shchelkunoff, S.V., Serdobintsev, G.V., Tarnetsky, V.V., Yakovlev, V.P., Zapryagaev, I.A., 1998, Present status of Budker INP 7 GHz pulsed magnicon. *Proc. Radio Frequency Workshop (RF 98), High Energy Density Microwaves, Pajaro Dunes, California, USA, AIP Conference Proceedings 474, 1999*, pp. 187-194.
- [461] Gold, S.H., Kinkead, A.K., Fliflet, A.W., Hafiza, B., Manheimer, W.A., 1996, Initial operation of a high-power frequency-doubling X-band magnicon amplifier. *IEEE Trans. on Plasma Science*, **PS-24**, 947-956.
- [462] Bottolier-Curtet, H., Gardelle, J., Bardy, J., Bonnafond, C., Devin, A., Gardent, D., Germain, G., Gouard, Ph., Labrousche, J., Launspach, J., Le Taillandier, P., de Mascureau, J., 1992, Progress in free electron maser experiments at CESTA. *Nucl. Instr. Meth.*, **A318**, 131-134.

- [463] Rullier, J.L., Gardelle, J., Labrouche, J., Le Taillandier, P., 1995, Strong coupling operation of a FEL amplifier with an axial magnetic field. *Nucl. Instr. Meth.*, **A358**, 118-121, and 1996, *Phys. Rev. E*, **53**, 2787-2794.
- [464] Gardelle, J., Labrouche, J., Marchese, G., Rullier, J.L., Villate, D., 1996, Analysis of the beam bunching produced by a free electron laser. *Physics of Plasmas*, **3**, 4197-4206.
- [465] Gardelle, J., Lefevre, T., Marchese, G., Rullier, J.L., Donohue, J.T., 1997, High-power operation and strong bunching at 3 GHz produced by a 35-GHz free-electron-laser amplifier. *Phys. Rev. Lett.*, **79**, 3905-3908.
- [466] Gardelle, J., Lefevre, T., Marchese, G., Rullier, J.L., Donohue, J.T., 1997, Measurements of microwave power and frequency in a pulsed free electron laser amplifier. *IEEE Trans. on Plasma Science*, **PS-25**, 1419-1424.
- [467] Donohue, J.T., Gardelle, J., Lefevre, T., Marchese, G., Padois, M., Rullier, J.L., 1999, Comparison of beam bunching in amplifier and SASE modes at the CEA-CESTA free-electron laser. *Nucl. Instr. Meth. in Phys. Research*, **A 429**, 202-208.
- [468] Lefevre, T., Gardelle, J., Marchese, G., J.L. Rullier, Donohue, J.T., 1999, Self-amplified spontaneous emission and bunching at 3 GHz in a microwave free-electron laser. *Phys. Rev. Lett.*, **82**, 323-326.
- [469] Donohue, J.T., Gardelle, J., Lefevre, T., Rullier, J.L., Vermare, C., Lidia, S.M., Meurdesoif, Y., 2000, Power generation in a resonant cavity using a beam bunched at 35 GHz by a free electron laser. *Nucl. Instr. and Meth. in Phys. Res.*, **A 445**, 307-312.
- [470] Lefevre, T., Gardelle, J., Rullier, J.L., Vermare, C., Donohue, J.T., Meurdesoif, Y., Lidia, S.M., 2000, Free-electron laser as a driver for a resonant cavity at 35 GHz. *Phys. Rev. Lett.*, **84**, 1188-1191.
- [471] Lefevre, T., Gardelle, J., Rullier, J.-L., Donohue, J.T., Lidia, S.M., 2000, Microwave production by a free-electron laser bunched beam driving a resonant cavity at 35 GHz. *IEEE Trans. on Plasma Science*, **PS-28**, 812-820.
- [472] Dodd, J.W., Marshall, T.C., 1990, Spiking Radiation in the Columbia free electron laser. *IEEE Trans. Plasma Science*, **PS-18**, 447-450.
- [473] Marshall, T.C., Cecere, M.A., 1994, A measurement of space-charge fields in a microwave free electron laser. *Physica Scripta*, **T52**, 58-60.
- [474] Cecere, M., Marshall, T.C., 1994, A free electron laser experiment on angular steering. *IEEE Trans. Plasma Science*, **PS-22**, 654-658.
- [475] Renz, G. Spindler, G., 1995, Status of the Stuttgart Raman free-electron laser project. *Nucl. Instr. Meth.*, **A358**, ABS13.
- [476] Ciocci, F., Bartolini, R., Doria, A., Gallerano, G.P., Giovenale, E., Kimmitt, M.F., Messina, G., Renieri, A., 1993, Operation of a compact free-electron laser in the millimeter-wave region with a bunched electron beam. *Phys. Rev. Lett.*, **70**, 928-931.
- [477] Gallerano, G.P., 1994, The free electron laser: state of the art, developments and applications. *Nucl. Instr. Meth.*, **A340**, 11-16.
- [478] Doria, A., Gallerano, G.P., Giovenale, G., Kimmitt, M.F., Messina, G., 1996, The ENEA F-CUBE facility: trends in rf driven compact FELs and related diagnostics. *Nucl. Instr. Meth.*, **A375**, ABS11-ABS13.
- [479] Hartemann, F., Buzzi, J.M., 1988, Experimental studies of a millimeter-wave free-electron laser. *Proc. 7th Int. Conf. on High-Power Particle Beams, Karlsruhe 1988*, eds., Bauer, W., Schmidt, W., Vol. II, 1287-1292.
- [480] Bongers, W.A., Militsyn, B.L., Bratman, V.L., Caplan, M., Denisov, G.G., van der Geer, C.A.J., Manintveld, P., Oomens, A.A.M., Plomp, J., Pluygers, J., Poelman, A.J., Riet, M., Saviolov, A.V., Smeets, P.H.M., Tito, C.J., Turk, G.H.B., Varfolomeev, A.A., Verhoeven, A.G.A., Urbanus, W.H., 2001, New results of the fusion-FEM in long-pulse set up. *Conf. Digest, 26th Int. Conf. on Infrared and Millimeter Waves, Toulouse, France*.
- [481] Bratman, V.L., Denisov, G.G., Ofitserov, M.M., Korovin, S.D., Polevin, S.D., Rostov, V.V., 1987, Millimeter-wave hf relativistic electron oscillators. *IEEE Trans. Plasma Science*, **PS-15**, 2-15.

- [482] Peskov, N.Yu., Bratman, V.L., Ginzburg, N.S., Denisov, G.G., Kolchugin, B.D., Samsonov, S.V., Volkov, A.B., 1996, Experimental study of a high-current FEM with a broadband microwave system. *Nucl. Instr. Meth.*, **A375**, 377-380.
- [483] Bratman, V.L., Denisov, G.G., Ginzburg, N.S., Kolchugin, B.D., Peskov, N.Y., Samsonov, S.V., Volkov, A.B., 1996, Experimental study of an FEM with a microwave system of a new type. *IEEE Trans. on Plasma Science*, **PS-24**, 744-749.
- [484] Arzhannikov, A.V., Bobylev, V.B., Sinitsky, S.L., Tarasov, A.V., Ginzburg, N.S., Peskov, N.Yu., 1995, Ribbon-FEL experiments at one-dimension distributed feedback. *Nucl. Instr. Meth.*, **A358**, 112-113.
- [485] Agafonov, M.A., Arzhannikov, A.V., Ginzburg, N.S., Peskov, N.Yu., Sinitsky, S.L., Tarasov, A.V., 1996, Powerful FEM generator driven by microsecond sheet beam. *Proc. 11th Conf. on High Power Particle Beams, Prague, BEAMS-96, Vol. 1*, pp. 213-216.
- [486] Agafonov, M.A., Arzhannikov, A.V., Ginzburg, N.S., Ivanenko, V.G., Kalinin, P.V., Kuznetsov, S.A., Peskov, N.Yu., Sinitsky, S.L., 1997, Generation of hundred joules RF-pulse at 4 mm wavelength by FEL with sheet beam. *Digest of Technical Papers, Workshop on High Power Microwave Generation and Pulse Shortening, Edinburgh, UK*, pp. 195-190.
- [487] Agafonov, M.A., Arzhannikov, A.V., Ginzburg, N.S., Ivanenko, V.G., Kalinin, P.V., Kuznetsov, S.A., Peskov, N.Yu., Sinitsky, S.L., 1998, Generation of hundred joules RF-pulse at 4 mm wavelength by FEM with sheet electron beam. *IEEE Trans. on Plasma Science*, **PS-26**, 531-535.
- [488] Agarín, N.V., Arzhannikov, A.V., Bobylev, V.B., Ginzburg, N.S., Ivanenko, V.G., Kalinin, P.V., Kuznetsov, S.A., Peskov, N.Yu., Sergeev, A.S., Sinitsky, S.L., Stepanov, V.D., 1999, Generation of hundred joules pulses of 4-mm radiation by planar FEM with two-dimensional distributed feedback. *Proc. 4<sup>th</sup> Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod*, ed. A.G. Litvak, Inst. of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 2000, **Vol. 2**, pp. 802-814.
- [489] Agarín, N.V., Arzhannikov, A.V., Bobylev, V.B., Ginzburg, N.S., Ivanenko, V.G., Kalinin, P.V., Kuznetsov, S.A., Peskov, N.Yu., Sergeev, A.S., Sinitsky, S.L., Stepanov, V.D., 2000, First operation of a powerful FEL with two-dimensional distributed feedback. *Nucl. Instr. and Meth. in Phys. Res.*, **A 445**, 222-229.
- [490] Ginzburg, N.S., Peskov, N.Yu., Zotova, I.V., Sergeev, A.S., Phelps, A.D.R., Cross, A.W., He, W., Ronald, K., Shpak, V.G., Yalandin, M.I., Shunailov, S.A., Ulmaskulov, M.R., 1999, Experimental observation of wiggler superradiance under group synchronism condition. *Nucl. Instr. Meth. in Phys. Research*, **A 429**, 94-100.
- [491] Ginzburg, N.S., Sergeev, A.S., Zotova, I.V., Shpak, V.G., Yalandin, M.I., Phelps, A.D.R., Cross, A.W., Wiggins, S.M., Tarakanov, V.P., 1999, Generation of powerful subnanosecond microwave pulses based on superradiance. *Proc. Int. University Conf. "Electronics and Radiophysics of Ultra-High Frequencies" (UHF-99)*, 1999, St. Petersburg, Russia, pp. 194-197.
- [492] Ginzburg, N.S., Zotova, I.V., Novozhilova, Yu.V., Sergeev, A.S., Phelps, A.D.R., Cross, A.W., Wiggins, S.M., Ronald, K., Shpak, V.G., Yalandin, M.I., Shunailov, S.A., Ulmaskulov, M.R., Tarakanov, V.P., 1999, Superradiance as method of generation of ultrashort microwave pulses. *Proc. 4<sup>th</sup> Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod*, ed. A.G. Litvak, Inst. of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 2000, **Vol. 2**, pp. 787-801.
- [493] Kaminsky, A.K., Kaminsky, A.A., Sarantsev, V.P., Sedykh, S.N., Sergeev, A.P., Ginzburg, N.S., Peskov, N.Yu., Sergeev, A.S., 1996, High efficiency FEL-oscillator with Bragg resonator operated in reversed guide field regime. *Nucl. Instr. Meth.*, **A375**, 215-218.
- [494] Ginzburg, N.S., Kaminsky, A.A., Kaminsky, A.K., Peskov, N.Yu., Sedykh, S.N., Sergeev, A.P., Sergeev, A.S., 1996, High-efficiency operation of the JINR-IAP Ka-band FEL-oscillator. *Proc. 3rd Int. Workshop on Strong Microwaves in Plasmas, Nizhny Novgorod*, 1997, Vol.2, pp. 782-790, and, 1998, *Nucl. Instr. Meth.*, **A407**, 167-171.

- [495] Ginzburg, N.S., Kaminsky, A.K., Kaminsky, A.A., Peskov, N.Yu., Sedykh, S.N., Sergeev, A.P., Sergeev, A.S., 1998, Theoretical and experimental comparison of FEL-oscillators with conventional and reversed guide field. *IEEE Trans. on Plasma Science*, **PS-26**, 536-541.
- [496] Ginzburg, N.S., Kaminsky, A.K., Kaminsky, A.A., Peskov, N.Yu., Sedykh, S.N., Sergeev, A.P., Sergeev, A.S., 1998, Single-mode and multimode operation conditions in JINR-IAP millimeter-wave FEL-oscillator. *IEEE Trans. on Plasma Science*, **PS-26**, 542-547.
- [497] Peskov, N.Yu., Ginzburg, N.S., Kaminskii, A.A., Kaminskii, A.K., Sedykh, S.N., Sergeev, A.P., Sergeev, A.S., 1999, High-efficiency narrow-band free-electron maser using a Bragg cavity with a phase discontinuity in the ripples. *Techn. Phys. Lett.*, **25**, 429-432.
- [498] Ginzburg, N.S., Kaminsky, A.K., Peskov, N.Yu., Sedykh, S.N., Sergeev, A.P., Sergeev, A.S., 1999, Development of high-efficiency FEL-oscillator for feeding high-gradient accelerating structures. *Proc. 4<sup>th</sup> Int. Workshop on Strong Microwaves in Plasmas*, Nizhny Novgorod, ed. A.G. Litvak, Inst. of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 2000, **Vol. 2**, pp. 815-820.
- [499] Ginzburg, N.S., Goldenberg C.A., Kaminsky, A.k., Peskov, N.Yu., Sedykh, S.N., Sergeev, A.P., 2000, Millimeter-wave FEL-oscillator with a new type Bragg resonator: advantages in efficiency and selectivity. *Nucl. Instr. and Meth. in Phys. Res.*, **A 445**, 253-256.
- [500] Ginzburg, N.S., Kaminsky, A.A., Kaminsky, A.K., Peskov, N.Yu., Sedykh, S.N., Sergeev, A.P., Sergeev, A.S., 2000, High-efficiency single-mode free-electron maser oscillator based on a Bragg resonator with step of phase of corrugation. *Phys. Rev. Lett.*, **84**, 3574-3577.
- [501] Akiba, T., Tanaka, K., Mokuno, M., Miyamoto, S., Mima, K., Nakai, S., Kuruma, S., Imasaki, K., Yamanaka, C., Fukuda, M., Ohigashi, N., Tsunawaki, Y., 1990, Helical distributed feedback free-electron laser. *Appl. Phys.Lett.*, **56**, 503-505.
- [502] Asakawa, M., Sakamoto, N., Inoue, N., Yamamoto, T., Mima, K., Nakia, S., Chen, J., Eujita, M., Imasaki, K., Yamanaka, C., Agari, T., Asakuma, T., Ohigashi, N., Tsunawaki, Y., 1994, Experimental study of a waveguide free-electron laser using the coherent synchrotron radiation emitted from electron bunches. *Appl. Phys.Lett.* **64**, 1601-1603.
- [503] Mizuno, T., Ootuki, T., Ohshima, T., Saito, H., 1995, Experimental mode analysis of the circular free electron laser. *Nucl. Instr. Meth.*, **A358**, 131-134.
- [504] Sakamoto, K., Kishimoto, Y., Watanabe, A., Kobayashi, T., Musyoki, S., Oda, H., Tokuda, S., Nakamura, Y., Kawasaki, S., Ishizuka, H., Sato, M., Nagashima, T., Shiho, M., 1992, MM wave FEL experiment with focusing wiggler, *Course and Workshop on High Power Microwave Generation and Applications*. Int. School of Plasma Physics, Varenna, 1991, eds., D. Akulina, E. Sindoni, C. Wharton, Editrice Compositori Bologna, 597-604.
- [505] Sakamoto, K., Kobayashi, T., Kawasaki, S., Kishimoto, Y., Musyoki, S., Watanabe, A., Takahashi, M., Ishizuka, H., Sato, M., Shiho, H., 1994, Millimeter wave amplification in a free electron laser with a focusing wiggler. *J. Appl. Phys.*, **75**, 36-42.
- [506] Lee, B.C., Kim, S.K., Jeong, Y.U., Cho, S.O., Cha, B.H., Lee, J., 1996, First lasing of the KAERI millimeter-wave free electron laser. *Nucl. Instr. Meth.*, **A375**, 28-31.
- [507] Ozaki, T., Ebihara, K., Hiramatsu, S., Kimura, Y., Kishiro, J., Monaka, T., Takayama, K., Whittum, D.H., 1992, First result of the KEK X-band free electron laser in the ion channel guiding regime. *Nucl. Instr. Meth.*, **A318**, 101-104.
- [508] Takayama, K., Kishiro, J., Ebihara, K., Ozaki, T., Hiramatsu, S., Katoh, H., 1994, 1.5 MeV ion-channel guided X-band free-electron laser amplifier. *Conf. Digest 19th Int. Conf. on Infrared and Millimeter Waves*, Sendai, JSAP Catalog No.: AP 941228, 3-4.
- [509] Takayama, K., Kishiro, J., Ebihara, K., Ozaki, T., Hiramatsu, S., Katoh, H., 1995, Experimental results on the 1.5 MeV ion channel guided X-band free electron laser. *Nucl. Instr. Meth.*, **A358**, 122-125.
- [510] Saito, K., Takayama, K., Ozaki, T., Kishiro, J., Ebihara, K., Hiramatsu, S., 1996, X-band prebunched FEL-amplifier. *Nucl. Instr. Meth.*, **A375**, 237-240.
- [511] Takayama, K., Monaka, T., 1996, Ion-channel guided X-band free-electron laser amplifier. *AIP Conference Proceedings*, No. 356, pp. 212-232.



- [512] Taccetti, J.M., Jackson, R.H., Freund, H.P., Pershing, D.E., Granatstein, V.L., 1999, A Ka-band CHI-wiggler free-electron maser: experimental results. *Nucl. Instr. Meth. in Phys. Research*, **A 429**, 116-120.
- [513] Orzechowski, T.J., Anderson, B.R., Clark, J.G., Fawley, W.M., Paul, A.C., Prosnitz, D., Scharlemann, E.T., Yarema, S.M., Hopkins, D.B., Sessler, A.M., Wurtele, J.S., 1986, High-efficiency extraction of microwave radiation from a tapered-wiggler free-electron laser. *Phys. Rev. Lett.*, **57**, 2172-2175.  
Allen, S.L., Scharlemann, E.T., *Proc. 9th Int. Conf. on High-Power Particle Beams*, edited by D. Mosher and G. Cooperstein (available from the National Technical Information Service, Springfield, VA22151), pp. 247.
- [514] Allen, S.L., Lasnier, C.J., Felker, B., Fenstermacher, M., Ferguson, S.W., Fields, S., Hooper, E.B., Hulsey, S., Makowski, M., Moller, J., Meyer, W., Petersen, D., Scharlemann, E.T., Stallard, B., Wood, R., 1993, Generation of high power 140 GHz microwaves with an FEL for the MTX experiment. *Proc. 1993 Particle Accelerator Conf.*, ed. S.T. Corneliussen, IEEE Piscataway, NJ, **Vol. 2**, pp. 1551-1553.  
Lasnier, C.J., Allen, S.L., Felker, B., Fenstermacher, M.E., Ferguson, S.W., Hulsey, S.D., Hooper, E.B., Jackson, M.C., Makowski, M.A., Meyer, W.H., Moller, J.M., Petersen, D.E., Sampayan, S.E., Stallard, B.W., Fields, W.F., Oasa, K., 1993, Burst mode FEL with the ETA-III induction linac. *Proc. 1993 Particle Accelerator Conf.*, ed. S.T. Corneliussen, IEEE Piscataway, NJ, **Vol. 2**, 1554-1556.
- [515] Allen, S.L., Brown, M.D., Byers, J.A., Casper, T.A., Cohen, B.I., Cohen, R.H., Fenstermacher, M.E., Foote, J.H., Hooper, E.B., Hoshino, K., Lasnier, C.J., Lopez, P., Makowski, M.A., Marinak, M.M., Meyer, W.H., Moller, J.M., Nevins, W.M., Oasa, K., Oda, T., Odajima, K., Ogawa, T., Ohgo, T., Rice, B.W., Rognlien, T.D., Stallard, B.W., Scharlemann, E.T., Thomassen, K.I., Wood, R.D., 1994, Nonlinear absorption of high power free-electron-laser-generated microwaves at electron cyclotron resonance heating frequencies in the MTX tokamak. *Phys. Rev. Lett.*, **72**, 1348-1351.
- [516] Allen, S.L., Casper, T.A., Fenstermacher, M.E., Foote, J.H., Hooper, E.B., Hoshino, K., Lasnier, C.J., Lopez, P., Makowski, M.A., Marinak, M.M., Meyer, W.H., Moller, J.M., Oasa, K., Oda, T., Odajima, K., Ogawa, T., Ogo, T., Rice, B.W., Rognlien, T., Stallard, B.W., Thomassen, K.I., Wood, R.D., 1992, Electron cyclotron resonance heating in the microwave tokamak experiment. *Proc. 14th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research*, Würzburg, Vol. 1, 617-625, (IAEA-CN-56/E-1-4).
- [517] Hartemann, F., Legorburu, P.P., Chu, T.S., Danly, B.G., Temkin, R.J., Faillon, G., Mourier, G., Trémeau, T., Bres, M., 1992, Long pulse high gain 35 GHz free-electron maser amplifier experiments. *Nucl. Instr. Meth.*, **A318**, 87-93.
- [518] Chu, T.S., Hartemann, F., Legorburu, P.P., Danly, B.G., Temkin, R.J., Faillon, G., Mourier, G., Trémeau, T., Bres, M., 1992, High-power millimeter-wave Bragg free-electron maser oscillator experiments. *Nucl. Instr. Meth.*, **A318**, 94-100.
- [519] Conde, M.E., Bekefi, G., 1992, Amplification and superradiant emission from a 33.3 GHz free electron laser with a reversed axial guide magnetic field. *IEEE Trans. Plasma Science*, **20**, 240-244 and *Nucl. Instr. Meth.*, **A318**, 109-113.
- [520] Volfbeyn, P., Ricci, K., Chen, B., Bekefi, G., 1994, Measurement of the temporal and spatial phase variations of a pulsed free electron laser amplifier. *IEEE Trans. Plasma Science*, **22**, 659-665.
- [521] Pasour, J.A., Gold, S.H., 1985, Free electron laser experiments with and without a guide magnetic field: a review of millimeter-wave free electron laser research at the NRL. *IEEE J. Quantum Electronics*, **QE-21**, 845-858.
- [522] Pershing, D.E., Seeley, R.D., Jackson, R.H., Freund, H.P., 1995, Amplifier performance of the NRL ubitron. *Nucl. Instr. Meth.*, **A358**, 104-107.
- [523] Karbushev, N.I., Mirnov, P.V., Sazhin, V.D., Shatkus, A.D., 1992, Generation of microwave radiation by an intense microsecond electron beam in an axisymmetric wiggler. *Nucl. Instr. Meth.*, **A318**, 117-119.

- [524] Liu, S., 1992, Recent development of FEL research activities in P.R. China. Conf. Digest 17th Int. Conf. on Infrared and Millimeter Waves, Pasadena, Proc., SPIE **1929**, 441 and private communication.
- [525] Chen, J., Wang, M.C., Wang, Z., Lu, Z., Zhang, L., Feng, B., 1991, Study of a Raman free-electron laser oscillator with Bragg reflection resonators. IEEE J. Quantum Electron., **QE-27**, 477-495.
- [526] Feng, B., Lu, Z., Zhang, L., Wang, M., 1994, Investigation of Raman free-electron lasers with a bifilar helical small-period wiggler. IEEE J. Quantum Electron., **QE-30**, 2682-2687.
- [527] Boehmer, H., Christensen, T., Camponi, M.Z., Hauss, B., 1990, A long-pulse millimeter-wave free electron maser experiment. IEEE Trans. Plasma Science, **PS-18**, 392-398.
- [528] Chen, J., Zheng, L., Zhang, Y., Yang, Z., 2000, A novel Smith-Purcell FEL. Int. J. of Infrared and Millimeter Waves, **21**, 1563-1567.
- [529] Chen, J., Zheng, L., Zhang, Y., Yang, Z., 2001, A novel smith-purcell free electron laser. Int. J. Electronics, **88**, 467-471.
- [530] Cheng, S., Granatstein, V.L., Destler, W.W., Levush, B., Rodgers, J., Antonsen, T.M., Jr., 1996, Experimental study of high-power, saturated amplification in a sheet-beam-small-period-wiggler FEL. Nucl. Instr. Meth., **A357**, 160-163.
- [531] Cheng, S., Destler, W.W., Granatstein, V.L., Antonsen, T.M., Jr., Levush, B., Rodgers, J., Zhang, Z.X., 1996, A high-power millimeter-wave sheet beam free-electron laser amplifier. IEEE Trans. on Plasma Sciences, **PS-24**, 750-757.
- [532] Elias, L.R., Ramian, G., Hu, J., Amir, A., 1986, Observation of single mode operation of a free electron laser. Phys. Rev. Lett., **57**, 424-427.
- Ramian, G., 1992, The new UCSB free-electron lasers. Nucl. Instr. Meth., **A318**, 225-229.
- [533] Wiggins, S.M., Whyte, C.G., He, W., Jaroszynski, D.A., Phelps, A.D.R., Cross, A.W., Ronald, K., 1999, Pulse propagation experiments in a free-electron maser. Conf. Digest 24<sup>th</sup> Int. Conf. on Infrared and Millimeter Waves, Monterey, California, USA, TU-E7.
- [534] Whyte, C.G., Jaroszynski, D.A., Cross, A.W., He, W., Ronald, K., Young, A., Phelps, A.D.R., 2000, Free electron maser amplifier experiments. Nucl. Instr. and Meth. in Phys. Res., **A 445**, 272-275.
- [535] Phelps, A.D.R., Cross, A.W., Jaroszynski, D.A., He, W., Whyte, C., Ginzburg, N.S., Peskov, N.Yu., 1997, A Ka-band Bragg free electron maser oscillator with axial guide magnetic field. Conf. Digest 22nd Int. Conf. on Infrared and Millimeter Waves, Wintergreen, Virginia, USA, pp. 17-18.
- [536] Ginzburg, N.S., Sergeev, A.S., Zotova, I.V., Novozhilova, Yu.V., Peskov, N.Yu., Konoplev, I.V., Phelps, A.D.R., Cross, A.W., Cooke, S.J., Aitken, P., Shpak, V.G., Yalandin, M.I., Shunailov, C.A., Ulmaskulov, M.P., 1997, Experimental observation of superradiance in millimeter-wave band. Nucl. Instr. Meth., **A393**, 352-355.
- [537] Cross, A.W., Ginzburg, N.S., He, W., Jaroszynski, D.A., Peskov, N.Yu., Phelps, A.D.R., Whyte, C.G., 1998, A 32 GHz Bragg free electron maser (FEM) oscillator with axial guide magnetic field. Nucl. Instr. Meth., **A407**, 181-186.
- [538] Cohen, M., Eichenbaum, A., Arbel, M., Ben-Haim, D., Kleinman, H., Draznin, M., Kugel, A., Yacover, I.M., Gover, A., 1995, Masing and single-mode locking in a free-electron maser employing prebunched electron beam. Phys. Rev. Lett., **74**, 3812-3815 and, 1996, Nucl. Instr. Meth., **A375**, 17-20.
- [539] Abramovich, A., Arensburg, A., Chairman, D., Eichenbaum, A., Draznin, M., Gover, A., Kleinman, H., Merhasin, I., Pinhasi, Y., Sokolowski, J.S., Yakover, Y.M., Cohen, M., Levin, L.A., Shahal, O., Rosenberg, A., Schnitzer, I., Shiloh, J., 1997, Lasing and radiation-mode dynamics in a Van de Graaff accelerator-free-electron laser with an internal cavity. Appl. Phys. Lett., **71**, 3776-3778 and, 1998, Nucl. Instr. Meth., **A407**, 16-20.
- [540] Abramovich, A., Canter, M., Gover, A., Sokolowski, J., Yakover, Y.M., Pinhasi, Y., Schnitzer, I., Shiloh, J., 1999, High spectral coherence in long-pulse and continuous free-electron laser: Measurements and theoretical limitations. Phys. Rev. Lett., **82**, 5257-5260.

- [541] Arbel, M., Eichenbaum, A.L., Pinhasi, Y., Lurie, Y., Tecimer, M., Abramovich, A., Kleinman, H., Yakover, I.M., Gover, A., 2000, Super-radiance in a prebunched beam free electron maser. Nucl. Instr. and Meth. in Phys. Res., **A 445**, 247-252.
- [542] Abramovich, A., Kleinman, H., Eichenbaum, A., Yakover, Y.M., Gover, A., Pinhasi, Y., 2000, Efficiency enhancement of free electron maser oscillator by mode selection with a prebunched electron beam. Appl. Phys. Lett., **76**, 16-18.
- [543] Van der Slot, P.J.M., Wittemann, W.J., 1993, Energy and frequency measurements on the Twente Raman free-electron laser. Nucl. Instr. Meth., **A331**, 140-143.