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Progress in the development of high-power millimeter- and submillimeter wave gyrotrons and of free electron masers

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Contents: At present, high power gyrotron oscillators are mainly used as generators for electron cyclotron resonance heating (ECRH) and diagnostics of magnetically confined plasmas for generation of energy by controlled thermonuclear fusion. 140 GHz gyrotrons with output power $P_{out} = 0.58$ MW in the Gaussian free space TEM_{00} mode with pulse length up to $\tau = 2.0$ s and efficiency $\eta = 34\%$ are commercially available. High order rotating TE-modes (e.g. $\mathrm{TE}_{22,6}$ at 140 GHz) are used as working modes in the cavities of these tubes. For plasma diagnostics higher frequencies are required. Therefore, gyrotron oscillators are designed for operation either at the second harmonic of the electron cyclotron frequency or at the fundamental cyclotron frequency with special pulsed high-field solenoids. $P_{out} = 40$ kW with $\tau = 40$ μs at $\eta = 4\%$ at frequencies up to 650 GHz have been achieved. In the case of gyrotron oscillators only slow frequency step tuning is possible by variation of the magnetic field (change of operating cavity mode). Fast and continuous frequency tuning by variation of the beam acceleration voltage is feasible for free electron masers (FEM). Record output parameters are: $P_{out} = 2$ GW, $\tau = 20$ ns, $\eta = 13\%$ at 140 GHz (LLNL) and $P_{out} = 15$ kW, $\tau = 20$ μs, $\eta = 5\%$ in the range from 120 to 900 GHz (UCSB).

Fortschritte bei der Entwicklung von Hochleistungs-Millimeter- und Submillimeter-Wellen Gyrotrons und Frei-Elektronen-Masern

Übersicht: Hochleistungs-Gyrotronoszillatoren werden derzeit vorwiegend als Generatoren für die Elektronen-Zyklotron-Resonanz-Heizung (ECRH) und Diagnostik von magnetisch eingeschlossenen Plasmen zur Erforschung der Energiegewinnung durch kontrollierte Kernfusion eingesetzt. 140 GHz Gyrotrons mit einer Ausgangsleistung von $P_{out} = 0.58$ MW in der Gaußschen Freiraumgrundmode TEM_{00} bei Pulslängen bis zu $\tau = 2.0$ s und Wirkungsgraden $\eta = 34\%$ sind kommerziell erhältlich. Als Arbeitsmoden im Röhrenresonator dienen dabei hohe, rotierende TE-Moden (z. B. $\mathrm{TE}_{22,6}$ bei 140 GHz). Zur Plasmadiagnostik werden höhere Frequenzen benötigt. Daher arbeiten die dazu vorgesehenen Gyrotronoszillatoren entweder bei der 2. Harmonischen der Elektronen-Zyklotronfrequenz oder bei der Grundfrequenz mit speziellen gepulsten Hochfeld-Magneten. Bisher wurde bei Frequenzen bis zu 650 GHz eine HF-Ausgangsleistung von $P_{out} = 40$ kW mit $\tau = 40$ μs und $\eta = 4\%$ erreicht. Die Ausgangsfrequenz von Gyrotronoszillatoren ist dabei nur langsam und stufenweise durch Veränderung des Magnetfeldes durchstimmbar (Übergang zu anderen Arbeitswellentypen im Resonator). Schnelle und kontinuierliche Frequenzdurchstimmbarkeit (über die Beschleunigungsspannung) ist beim Frei-Elektronen-Maser (FEM) gegeben. Rekordausgangsparameter sind hier: $P_{out} = 2$ GW, $\tau = 20$ ns, $\eta = 13\%$ bei 140 GHz (LLNL) und $P_{out} = 15$ kW, $\tau = 20$ μs, $\eta = 5\%$ im Bereich von 120 bis 900 GHz (UCSB).

1 Introduction

Fast wave devices in which the phase velocity v_{ph} of the electromagnetic wave is greater than the speed of light c, generate or amplify coherent electromagnetic radiation by stimulated emission of bremsstrahlung from a beam of relativistic electrons. The electrons radiate because they undergo oscillations transverse to the direction of beam motion by the action of an external force (field). For such waves the electric field is mainly transverse to the propagation direction. The condition for coherent radiation is 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 [1]

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

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

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

$$\Omega_c = \Omega_{c0}/\gamma \quad \text{with} \quad \Omega_{c0} = eB_0/m_0 \quad \text{and}$$

$$\gamma = [1 - (v/c)^2]^{-1/2} \tag{2}$$

where e and m_0 are the charge and rest mass of an electron, γ is the relativistic factor, and B_0 is the magnitude of the guide magnetic field. A group of relativistic electrons gyrating in a strong magnetic field will radiate coherently due to bunching caused by the relativistic mass dependence of their gyration frequency. Bunching is achieved because, as an electron loses energy, its relativistic mass decreases and it thus gyrates faster. The strength of the magnetic field determines the value of the radiation frequency.

Gyrotron oscillators (gyromonotrons) are devices which usually utilize only weakly relativistic electron beams (< 100 kV) with high transverse momentum (pitch angle $\alpha = v_\perp / v_z > 1$). 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 on one of its harmonics:

$$\omega \cong s\Omega_c, \quad s = 1, 2, \ldots \tag{3}$$

In the case of cylindrical cavity tubes 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 electron bunches in the retarding phase. The Doppler term $k_z v_z$ is of the order of the gain width and is small compared with the radiation frequency. Cyclotron harmonic operation reduces the required magnetic field for a given frequency by the factor s. The predicted efficiency for gyrotrons operating at higher harmonics ($s = 2$ and 3) are comparable with those operating at the fundamental frequency [2].

Many other types of microwave sources are also based on the ECM instability, such as quasi-optical gyrotron with Fabry-Perot-type resonator, gyro-klystron, gyro-travelling wave amplifier (gyro-TWA) or gyro-backward wave oscillator (gyro-BWO). Cyclotron maser devices operating in the relativistic Doppler-shifted regime where the axial bunching mechanism can substantially offset the azimuthal bunching are called cyclotron autoresonance masers (CARMs) [1].

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

$$\Omega_b = k_w v_z, \quad k_w = 2\pi / \lambda_w \tag{4}$$

The operating frequency of such devices, an example of which is the free electron maser (FEM) [3, 4], 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 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 pondermotive wave, a wave caused by "beating" of the electromagnetic wave with the spatially periodic wiggler field.

In the case of the ECMs and FEMs unlike most conventional microwave sources, the radiation wavelength is not determined by the characteristic size of the interaction region. Such fast wave devices employ overmoded interaction circuits and thus are capable of producing very high power radiation at centimeter, millimeter, and submillimeter wavelengths.

This paper reports about the current status of the development of high power millimeter- and submillimeter wave gyrotrons ($s = 1$ and 2) and of FEMs.

2 Gyrotrons for fusion plasma heating

At present, gyrotron oscillators are mainly used as high power millimeter wave sources for electron cyclotron resonance heating (ECRH) and diagnostics of magnetically confined plasmas in controlled thermonuclear fusion research. Long-pulse and CW gyromonotrons utilizing open-ended cylindrical resonators which generate output powers of 100–400 kW per unit, at frequencies between 28 and 84 GHz, have been used very successfully for plasma formation, ECRH and local current density profile control by noninductive current drive (ECCD) in tokamaks [5] and stellarators [6]. Gyrotron complexes with total power of up to 4 MW are used. The confining toroidal magnetic fields in present day fusion machines are in the range of $B_0 = 1 - 3.5$ Tesla. As experimental devices become larger and operate at higher magnetic fields ($B_0 = 5$T) and higher plasma densities ($n_{e0} = 1 - 2 \cdot 10^{20}/\text{m}^3$) in steady state, present and forthcoming ECRH requirements call for gyrotron output powers of at least 1 MW, CW at frequencies ranging from 120–180 GHz. Since efficient ECRH and ECCD needs axisymmetric, narrow, pencil-like mm-wave beams with well defined polarization, single mode emission is necessary in order to generate a TEM_{00} Gaussian beam mode at the plasma torus launching antenna.

Table 1. Present development of 140 GHz gyrotron oscillators for fusion plasma EC wave applications (pulse length ≧0.5 ms)

Institution	Frequency	Mode		Power	Efficiency	Pulse length
	[GHz]	cavity	output	[MW]	[%]	[s]
KfK, PHILIPS,	140	TE_{03}	TE_{03}	0.12	23	0.4
KfK, Karlsruhe	140	$\text{TE}_{10,4}$	$\text{TE}_{10,4}$	0.69	27	0.005
SALUT, IAP, Nizhny Novgorod	140	$\text{TE}_{22,6}$	TEM_{00}	0.9	36	0.4
				0.5	33	2.0
TORIY, Moscow, IAP, Nizhny Novgorod	140	$\text{TE}_{22,5}$	TEM_{00}	0.97	34	0.3
				0.58	34	2.0
VARIAN, Palo Alto	140	$\text{TE}_{02/03}$	TE_{03}	0.1	27	CW
	140	$\text{TE}_{15,2}$	$\text{TE}_{15,2}$	0.26	28	5.0
				0.33	30	3.5
				1.04	38	0.0005

Single mode mm-wave gyrotron oscillators capable of high average power, 0.5–1 MW per tube, in long-pulse or CW operation, are currently under development in several scientific and industrial laboratories. The present state of the art at 140 GHz is given in Table 1 [7]. 140 GHz gyrotrons with output power $P_{out} = 0.58$ MW, pulse length $\tau = 2.0$ s and efficiency $\eta = 34\%$ are commercially available in Russia. The corresponding parameters of a 166 GHz gyrotron are $P_{out} = 0.5$ MW, $\tau = 0.7$ s and $\eta = 30\%$. High order rotating TE-modes (e.g. $\mathrm{TE}_{22,6}$ at 140 GHz) are used as working modes in the cavities of the tubes. An internal quasi-optical mode transducer generates the TEM_{00} output mode with an efficiency of 90–95% [8]. At KfK Karlsruhe the following gyrotron parameters have been achieved: 140 GHz, 120 kW, 0.4 s, 23% (TE_{03} mode) and 140 GHz, 690 kW, 5 ms, 27% ($\mathrm{TE}_{10,4}$ mode). The worldwide first ECRH and ECCD experiments at 140 GHz were performed in the Stellarator W7-AS at IPP Garching using the KfK-TE_{03}-mode tube [9].

With increasing operating frequency, power level and pulse duration a number of problems arise which necessitate significant changes in the gyrotron design approach. Design trade-offs and operating limits are necessary. The main difficulties encountered in the realization of efficient megawatt CW mm-wave gyrotrons for fusion reactors (120 GHz to 180 GHz) are connected with [7]:

- formation of an electron beam with sufficient orbital energy ($\alpha \geqq 1.5$) and small velocity spread (electron gun design)
- propagation of the electron beam in the tube, spurious oscillations in the beam tunnel between the electron gun and the interaction cavity, voltage depression (dependant on the ratio of electron beam radius to cavity radius), space charge effects and beam instabilities
- ohmic wall losses in the cavity (cavity heating)
- mode selectivity in a highly overmoded cavity, single mode operation, sufficient mode separation of working mode from competing modes
- unwanted mode conversion in the electrodynamic system of the tube
- thermal loading of the electron beam collector
- heating of the output window, selection of output mode
- enhancement of total system efficiency up to 50–60% employing a depressed collector.

3 Very high frequency gyrotrons

The development of high power gyrotrons for the short millimeter- and submillimeter-wave region is important for application such as ECRH on high-field tokamak experiments with confining magnetic field $B_0 \geqq 10$ T [10], for active plasma diagnostics such as mm-wave scattering to determine velocity distributions of ions, heat pulse propagation experiments and to study drift instabilities [11], as well as for radar and spectroscopy [2, 12]. During the past several years impressive results have been obtained with pulsed and CW gyrotrons designed for operation at the second harmonic ($s = 2$) of the electron cyclotron frequency employing superconducting [13] or Bitter magnets [14]. The most impressive recent results are given in Table 2 [7].

Fundamental cyclotron resonance interaction has been studied using a special pulsed solenoid for $B_0 = 14–27$ T [11] or a Bitter magnet rebuilt to operate at up to $B_0 = 14$ T [10]. Key issues to be addressed are: stability of electron beams with compression ratio $\geqq 40$, mode competition in cavities with $D/\lambda \geqq 20$, improved cavity design, and step-tuning of frequency up to 327 GHz. Table 3 (see Pag 54) summarizes the present capabilities and performance parameters of such millimeter wave gyrotrons with output power $\geqq 1$ kW [7].

Operating at both the fundamental and the second harmonic of the electron cyclotron frequency enables the gyrotron to act as a medium power (several 100 W), step tunable, millimeter- and submillimeter wave source in the wide frequency range from 150 to 640 GHz [15].

4 Free electron masers

In the case of gyrotron oscillators only slow frequency step tuning is possible by variation of the magnetic field (change of operating cavity mode). However, the FEM

Table 2. Capabilities and performance parameters of mm- and submillimeter-wave gyrotrons operating at the second harmonic of the electron cyclotron frequency (output power $\geqq 1$ kW)

Institution	Frequency [GHz]	Mode	Power [kW]	Efficiency [%]	Pulse length [ms]
IAP, N. Novgorod	157	TE_{03}	2.4	9.5	CW
	250	TE_{02}	4.3	18	CW
	250	TE_{65}	1	5	CW
	326	TE_{23}	1.5	6	CW
MIT, Cambridge	209	TE_{92}	15	3.5	0.001
	241	$\mathrm{TE}_{11,2}$	25	6.5	0.001
	302	TE_{34}	4	1.5	0.0015
	339	$\mathrm{TE}_{10,2}$	4	3	0.0015
	363	$\mathrm{TE}_{11,2}$	7	2.5	0.0015
	417	$\mathrm{TE}_{10,3}$	15	6	0.0015
	457	$\mathrm{TE}_{15,2}$	7	2	0.0015
	467	$\mathrm{TE}_{12,3}$	22	3.5	0.0015
	503	$\mathrm{TE}_{17,2}$	10	5.5	0.0015
UNIVERSITY, Fukui	383	TE_{26}	3	3.7	1
	402	TE_{55}	2	3	1

appears potentially capable of fulfilling all the requirements for a frequency agile high power mm-wave source. Rapid tunablility over more than ±5% could be obtained by variation of the beam energy. The interaction occurs in a cavity operating in low-order modes, which have very good coupling to a Gaussian output beam. The relatively low RF wall loading and the use of high electron beam energy (>0.5 MeV) are compatible with a high unit power if the electron beam interception could be maintained at an acceptable low level. A survey of FEM development is presented in Table 4 (for references [16]). The most impressive output parameters are $P_{out} = 2$GW, $\tau = 20$ ns, $\eta = 13\%$ at 140 GHz (LLNL) and $P_{out} = 15$ kW, $\tau = 20\ \mu$s, $\eta = 5\%$ in the range from 120 to 900 GHz (UCSB).

The electrostatic accelerator allows true CW operation and has the potential of achieving efficiencies in the 50% range through energy recovery (but very good beam quality is required). Table 5 summarizes the design parameters of the planned FOM-FEM experiment [17].

Table 3. Capabilities and performance parameters of pulsed millimeter- and submillimeter-wave gyrotron oscillators operating at the fundamental electron cyclotron resonance (output power ≥ 1 kW)

Institution	Frequency [GHz]	Mode	Power [MW]	Efficiency [%]	Pulse length [μs]
MIT, Cambridge	148	$TE_{16,2}$	1.3	39	3
	188	$TE_{18,3}$	0.6		3
	|	|	|		|
	225	$TE_{23,3}$	0.37		3
	231	$TE_{38,5}$	1.2	20	3
	236	$TE_{21,4}$	0.4		3
	|	|	|		|
	287	$TE_{28,4}$	0.2		3
	280	$TE_{25,13}$	0.78	17	3
	267	$TE_{22,5}$	0.537	19	3
	|	|	|		|
	320	$TE_{29,5}$	0.4	20	3
	327	$TE_{27,6}$	0.375		3
IAP, Nizhny Novgorod	250	$TE_{20,2}$	0.3	31	30–80
	350		0.13	17	30–80
	430		0.08	10	30–80
	500		0.1	8.2	30–80
	540		0.06	6	30–80
	650		0.04	4	40

Table 4. State-of-the-art of millimeter- and submillimeter wave FEMs

Institution	Frequency [GHz]	B_w [T]	λ_w [mm]	Mode	Power [MW]	Efficiency [%]	Gain [dB]	Voltage [MV]	Current [kA]	Accelerator	Pulse-Length [μs]	Type
ENEA Frascati	85–200	0.63	25	$TE_{01}^{\square}$	0.0015	$1.6 \cdot 10^{-4}$		2.3	0.004	Microtron	0.18	oscil.
EP Palaiseau	120	0.03	20	TE_{11}°	11.5	6.4		0.6	0.3	Electrostatic	0.02	superrad.
FOM Rijnhuizen	≥ 2700	0.04	65		0.0001	$2 \cdot 10^{-8}$	20	25	0.0002	RF LINAC	0.03	ampl.
ILE Osaka	250				0.6			4	0.5	Ind. LINAC		
JAERI, Ibaraki	35.5	0.18	45	TE_{11}°			36	0.70	0.10 (0.38)	Ind. LINAC	0.08	ampl.
LLNL, Livermore	34.6	0.37	98	$TE_{01}^{\square}$	1000	34	52	3.5	0.85 (4.0)	Ind. LINAC	0.02	ampl.
	140	0.17	98	TE_{11}°	2000	13.3	58	6.0	2.5 (3.0)	Ind. LINAC	0.02	ampl.
MIT, Cambridge	9.3	0.02	33	TE_{11}°	0.1	10	6	0.18	0.0055	Electrostatic	0.02	ampl.
	27.5	0.05	30	TE_{11}°	1	10.3	–	0.32	0.03 (0.05)	Electrostatic	1	oscil.
	33.4	0.15	32	TE_{11}°	61	27	50	0.75	0.3	Electrostatik	0.03	ampl.
	35.2	0.05	30	TE_{11}°	0.8	8.6	26	0.31	0.03 (0.05)	Electrostatik	1	ampl.
NRL, Washington D.C.	12.5–16.5	0.1	30	$TE_{01}^{\square}$	0.7	3		0.25	0.1			ampl.
	23–31	0.06	40	TE_{01}°	4	3		0.7	0.2	Ind. LINAC	0.035	ampl.
	35	0.14	30	TE_{11}°	17	3.2	50	0.9	0.6	Pulse Line	0.02	ampl.
	75	0.08	30	TE_{11}°	75	6	50	1.25	1.0	Pulse Line	0.02	ampl.
TRW, Redondo Beach	35	0.16	20	$TE_{01}^{\square}$	0.1	9.2		0.3	0.004	Electrostatic	10	oscil.
	35	0.16	20	$TE_{01}^{\square}$	0.1	9.2	2	0.29	0.0001	Electrostatic	10	ampl.
UCSB Santa Barbara	120–900	0.24	32		0.015	5		6	0.002	Electrostatic	20	oscil.

Table 5. Design parameters of the planned FOM-FEM [17]

power	1 MW – sufficient for FEM demonstration – comparable with biggest gyrotrons
frequency	130 GHz, 200 GHz, 250 GHz – future use on fusion devices – higher than gyrotron frequencies
ms-scale tunability	10% via e-beam energy (high-voltage) – to demonstrate advantage of FEM – for tracking of plasma disruptions
gain	3 (saturation) – to limit intra-cavity power ≈ 7 (small signal gain) – fast start-up (≈ 1 μs)
extraction eff., η	5%
pulse duration	100 ms – eventually CW but at first 100 ms to avoid severe cooling problems
power efficiency	$\approx 60\%$ (grid- > MMW power)
electron beam	– 12 A, $V = 2.0$, 1.75, 1.35 MeV for $f = 250$, 200, 130 GHz
undulator	– period = 40 mm, 2 sections – section 1: 20 cells, $B = 0.20$ T – gap: 25 mm – section 2: 14 cells, $B = 0.16$ T

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