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RECENT ADVANCES IN GYROTRONS AND FREE ELECTRON LASERS (Invited Talk)

R. J. Temkin

Plasma Fusion Center, Massachusetts Institute of Technology
Cambridge, MA

Abstract

The status of gyrotrons and free electron lasers operating at microwave, millimeter wave and submillimeter wavelengths is reviewed. These novel, fast wave devices are making rapid progress, opening up a variety of new applications.

Introduction

An overview will be presented of recent advances in the physics and technology of millimeter wave gyrotrons and free electron lasers. These novel devices are both promising sources of high power coherent radiation. Recent progress on the gyrotron includes industrial development of a 100kW, CW gyrotron oscillator at 140GHz. Research results include pulsed oscillator operation at power levels approaching 1MW at 140 to 240GHz at M.I.T. and power levels above 10kW extending into the submillimeter wave region. Gyrotron amplifiers, including the gyro-TWT and the gyroklystron, are also promising but are not yet fully demonstrated, particularly at high frequency. Other novel devices include the gyromagnetron, large orbit harmonic gyrotron and the relativistic gyrotron (Cyclotron Autoresonance Maser). The free electron laser (FEL) has also shown dramatic progress recently, including a 1GW amplifier with 40% efficiency using a 3.5MW, 800A beam at Lawrence Livermore National Lab. A Raman regime, X-band FEL experiment at M.I.T. using a guide magnetic field has achieved 100kW amplifier outputs with good phase stability. State of the art FEL experiments are now planned at several laboratories, including an 18GHz experiment at NRL, a 35GHz experiment at TRW and a 60GHz experiment at Hughes.

The Gyrotron

The emission from a gyrotron is near the Doppler shifted cyclotron resonance. With ω representing the angular frequency and k the wave vector of the radiation, the condition may be stated $\omega - kv = n\omega_c$ where n is an integer representing the harmonic number, v the electron axial velocity, ω_c the relativistic electron gyrofrequency, $\omega_c = eB/\gamma m_e$, with e and m_e the electron charge and rest mass, B the magnetic field strength, k the axial wavenumber and γ the relativistic factor given by $\gamma = (1-\beta^2)^{-1/2}$ where β is the electron velocity normalized to the speed of light (c). In addition, the frequency ω must also be an allowed mode of the guiding structure or resonator. The linear and nonlinear theory of the gyrotron has been recently reviewed in several articles [1, 2, 3].

Recent Results

Significant progress has been made over the past decade in the development of high power gyrotrons that can be used for electron cyclotron resonance heating (ECRH) of fusion experiments. Earlier results include cw devices that have generated powers ranging up to 200 kW at 28 GHz [4]. More recently, 200 kW cw has been produced at 60 GHz [5], and long pulse gyrotrons operating at 84 GHz have generated comparable power [6]. In addition, short pulse gyrotrons have produced powers in excess of 100 kW at 35 GHz [7], 45 GHz, 100 GHz [8], and 140 GHz [9]. Very recently, a 100 kW, 140 GHz cw gyrotron has been demonstrated at Varian Associates by K. Felch and coworkers [10]. Intensive research on 120 to 150 GHz gyrotrons is also now underway at the CRPP, Lausanne, Switzerland and the KfK, Karlsruhe, FRG.

M.I.T. Gyrotron Research

A variety of experiments have been carried out at M.I.T. using the apparatus shown in Fig. 1. This gyrotron uses a magnetron injection gun constructed by Varian Associates, Inc. The magnet used is a water cooled, copper magnet of the Bitter type capable of operation to over 10 T. Other parameters of this gyrotron are operation at 80 kV, up to 50 A, 3 microsecond pulse length (but scalable to cw), and design output power of 1MW at 140 GHz.

Experimental Results

In the first set of experiments, the $TE_{m,2,1}$ modes were investigated. Of particular interest, because of its isolation from nearby competing modes, was the $TE_{15,2,1}$ mode.

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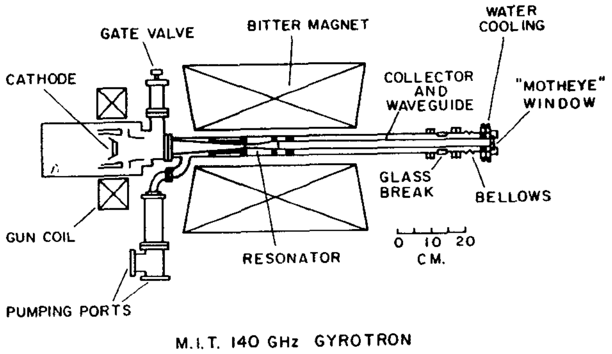

Fig.1

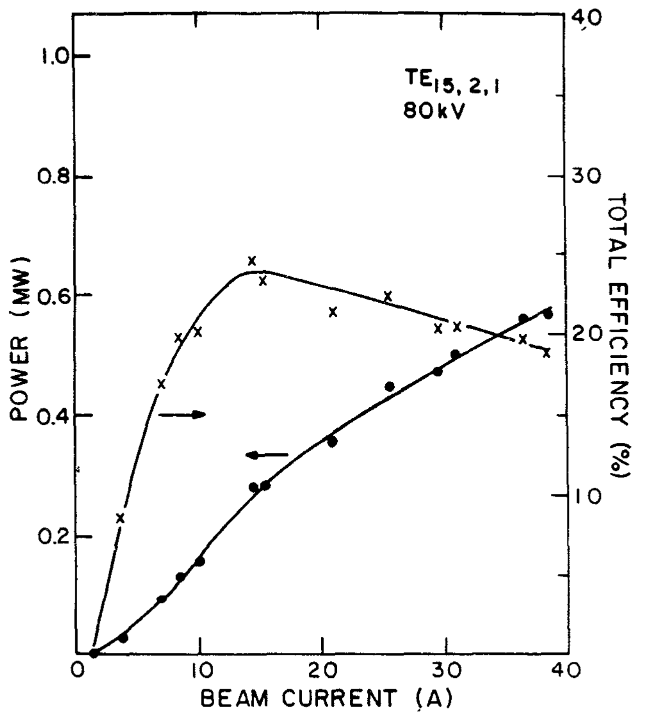

Fig.2

Stable operation was achieved in the $TE_{15,2,1}$ at 140.8 GHz. Output powers up to 645 kW, and peak efficiencies of 24% were obtained with single mode emission. In addition, other $TE_{m,2,1}$ modes ranging from the $TE_{12,2,1}$ at 119.2 GHz to the $TE_{16,2,1}$ at 147.9 GHz. were also strongly excited. Current monitors indicated that there was no interception, and that the beam was reaching the collector. Deliberate interception indicated that the outer beam diameter was in agreement with theory.

Figure 2 shows the optimum power and total efficiency achieved in the $TE_{15,2,1}$ as measured with a Scientech calorimeter [11]. The starting current is about 1 A, and peak efficiencies are achieved at 15 A. Self-consistent theory is in agreement with this data up to about 10 A. Beyond this current the theoretical efficiency continues to increase, peaking at 38% at 35 A, while the measured efficiency saturates. The observed degradation of efficiency at higher powers may be due to mode competition from the $TE_{11,3,1}$ mode, which was observed at 136.4 GHz. This is also supported by a careful mapping of the region of oscillation for the $TE_{15,2,1}$ mode, which indicates that the highest powers occur along the boundary with the $TE_{11,3,1}$ region. It was found that the gyrotron was extremely sensitive to the magnetic field settings. Careful optimization of these fields was required to achieve our best power of 645 kW, which was obtained at 80 kV and 35 A.

A search for harmonic emission was also conducted. Second harmonic radiation was only detected at lower magnetic fields. In particular, a 219.4 GHz signal was detected at 4.56 T. The general lack of harmonic emission is probably due to the dense fundamental spectrum, which would tend to prevent excitation of harmonic modes.

The Free Electron Laser

The free electron laser utilizes an axial electron beam of velocity v_z (and relativistic factor γ) passing through a magnetostic wiggler field of period $\lambda_w, k_w = 2\pi/\lambda_w$, to obtain emission at (ω_s, k_s) given by:

$$\omega_s - k_z v_z = k_w v_z$$

where k_z is the axial wavenumber of the wave at frequency ω_s. For $\gamma \gg 1$, the emission wavelength is $\lambda_s \approx \lambda_w/2\gamma^2$. Free electron lasers operating at microwave and millimeter waves often use waveguide. Reviews of the field have been published recently [12, 13].

Recent Results

A number of important results have been obtained recently in the microwave and millimeter wave bands. These include emission at 1 GW power levels, 10–15 ns pulse length at 34.6 GHz on the ELF experiment of the ETA accelerator at Lawrence Livermore National Laboratory (3.5 MV, 800 A) [14]. A Raman FEL with a guide field built by G. Bekefi and coworkers at M.I.T. has achieved tunability from 7–21 GHz with 100 kW output at up to 10% efficiency using a 160 kV, 5 A beam [15]. Progress on microwave FEL's has also been reported by the Columbia group at a wavelength of 2.5 mm [16] and by the NRL group [17, 18].

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