RELATIVISTIC ELECTRON BEAM INTERACTIONS FOR GENERATION OF HIGH POWER AT MICROWAVE FREQUENCIES*

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Abstract

Several coherent emission processes operative within high-power, relativistic electron beams have been studied during the past few years. The spectral range of interest extends from centimeter to submillimeter wavelengths. Effort within this field is presently concentrated in three areas: exploratory development of the electron cyclotron maser (gyrotron) for millimeter-wave sources; a basic study of scattering mechanisms whereby incident microwave radiation is Doppler-shifted to higher frequency; and the extension of conventional microwave sources to the gigawatt level using pulsed power techniques. The field is reviewed with emphasis on the several mechanisms employed and results of recent theoretical and experimental investigations.

Introduction

During the last few years, the application of intense, relativistic-electron beams to the generation of electromagnetic radiation at wavelengths ranging from 10 cm down to fraction of a millimeter has enabled significant advances to be made in peak power capabilities. The purpose of this review is to summarize the status of these advances and to describe briefly the nature of the several mechanisms involved.

Electron Cyclotron Maser (Gyrotron)

The most important class of experiments are those based on the electron cyclotron maser, called the gyrotron in the Soviet Union. This device represents a major breakthrough for frequencies above 10 - 20 GHz and extending to 300 GHz or more. Basic understanding of the device proceeded slowly following the early concepts and experiments.[1] However, recent developments in this country and in the Soviet Union have shown that the cyclotron maser is ready for practical development.

The electron cyclotron maser ideally consists of a cloud of monoenergetic electrons in a fast wave structure such as a metallic tube or waveguide, with electron velocity transverse to an applied axial magnetic field. Such an electron ensemble can react unstably with a fast microwave signal propagating through the waveguide. Initially, the phases of the electrons in their cyclotron orbits are random, but phase bunching can occur because of the realtivistic mass change of the electrons. Those electrons that lose energy to the wave become lighter and accumulate phase lead while those electrons that gain energy from the wave become heavier and accumulate phase lag. This can result in a phase bunching such that the electrons radiate coherently and amplify the electromagnetic wave. Energy transfer from the electrons to the wave is optimized when the frequency is slightly higher than the electron cyclotron frequency (or its harmonics).

The cyclotron maser emits radiation at a wavelength determined by the strength of an applied magnetic field, and not by the dimensions of a resonant structure. Thus, unlike other microwave generators, the internal dimensions of the device may be large compared to the wavelength, and high power handling capability (up to megawatts) becomes compatible with operation at millimeter wavelengths. Indeed, the highest recorded millimeter-wave power, both peak and average, has been achieved with cyclotron masers.

New impetus to the study of the cyclotron maser mechanism came from the research into microwave emission from intense, relativistic electron beams, with beam power in the range of 10^9 - 10^{12} W. A number of experiments, mainly at the Naval Research Laboratory, demonstrated that intense microwave radiation could be produced by perturbing the externally applied magnetic field which guided the electron beam. This magnetic field perturbation took a number of forms, viz. a periodic magnetic ripple of limited length, a nonadiabatic convergence of the magnetic field lines, and a nonadiabatic divergence of the magnetic field lines. A definitive identification of the cyclotron maser mechanism as the major source of microwave generation in these experiments was made through two salient observations. First, it was established that the modal structure of the microwaves corresponded to that expected in the cyclotron maser instability. Secondly, it was demonstrated that wave growth took place in a region of uniform magnetic field after the electron beam had encountered the magnetic perturbation. The perturbation in the magnetic field provided the required distribution of transverse kinetic energy.

Table 1 displays the maximum attained peak power levels produced with intense relativistic electron beams through the cyclotron maser process. It is especially noteworthy that these record peak powers were produced at millimeter wavelengths as well as in the more usual microwave bands.

Table 1 - Peak Power from Cyclotron Masers Using Intense Beams.

Wavelength (mm)	40	20	8	4
Peak Power (MW)	900	350	8	2
Voltage (MV)	3.3	2.6	0.6	0.6
Current (kA)	80	40	15	15

In addition to the high power levels in these intense beam experiments, it was also demonstrated[2] that the emission possessed a high degree of temporal and spatial coherence. Furthermore, the cyclotron maser was operated as a distributed-interaction amplifier[2] which could be tuned magnetically over a wide frequency range. The amplifier configuration is shown in Fig. 1. It should be noted that a distributed-interaction device has the advantage of tunability over a wide frequency range and, in addition, allows dissipation of greater power as compared with a short resonator. Thus, its realization has considerable practical importance.

Experimental research on cyclotron masers using intense relativistic electron beams is summarized in

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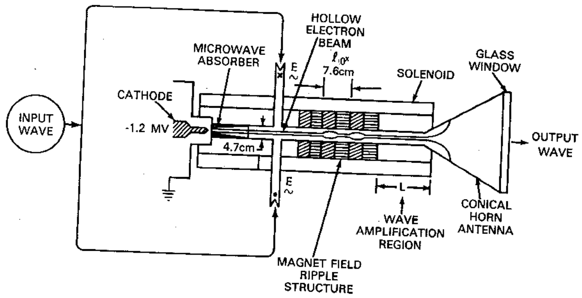

Fig. 1 - Cyclotron maser distributed-interaction amplifier using an intense relativistic electron beam.[2] Input signal from magnetron was coupled into the drift tube in the TE_{01} mode. The ripple structure consisted of alternating iron and aluminum rings which perturbed the magnetic field lines and imparted large transverse energy into the growing TE_{01} wave. The length of the system from cathode to output window was about 3 meters.

review papers by Hammer, et al.[3] and by Granatstein, et al.[4] Equally important as the experimental results was the stimulation they provided for theoretical studies. We note especially the nonlinear analysis of the saturation of the cyclotron maser instability by phase trapping,[5] and the subsequent self-consistent analysis,[6] which generalized the first result to include saturation by energy depletion as well as by phase trapping. The latter work is useful not only in interpreting intense relativistic electron beam experiments but also in developing practical cyclotron maser tubes driven by electron beams with more conventional parameters.

The lead in development of practical cyclotron masers using electron beams with conventional voltage and current values has been taken by a group working at the Gork'ii State University (USSR), where the device has been given the name "gyrotron". In contrast to the cyclotron maser work in the U.S.A. after 1970 which centered around the intense relativistic electron beam technology outlined above and which was very much in the nature of a basic laboratory study, the Soviet work comprised a sustained development effort leading to practical power tubes at millimeter and submillimeter wavelengths. The key element in achieving practical devices characterized by high efficiency was in careful design of the electron gun. In the Gork'ii studies a cross field, or so-called magnetron injection gun was used to launch an annular beam with a large fraction of energy transverse to the axis and with minimum energy spread. These guns employed thermionic cathodes for CW and long-pulse operation.

Table 2 summarizes the results published to date on tubes using superconducting magnets. Kisel', et al.[8] describe a device in a magnetic field of only 6 kG which produces 9 mm CW power of 10 kW with 40% efficiency, and pulsed power of 30 kW at 43% efficiency. Recent reports from Soviet scientists who use the gyrotrons for RF heating of tokamak plasmas indicate that millimeter wave gyrotrons are now available with power at the level of hundreds of kilowatts.

The success achieved in the USSR in realizing high efficiency gyrotrons has now stimulated parallel work

Table 2 - Reported Gyrotron CW Results.[7]

Cylindrical Cavity Mode (TE)	021	031	231	231
Wavelength (mm)	2.8	1.9	2.0	0.9
Harmonic No.	1	2	2	2
B-Field (T)	4.0	2.9	2.9	6.1
Voltage (kV)	27	18	16	27
Output (kW)	12	2.4	7*	1.5
Exp. Eff. (%)	31	10	15	6
Theor. Eff. (%)	36	15	20	5
*Pulsed				

in the U.S.A. Under ERDA sponsorship, Varian Associated are currently developing a tube at 28 GHz with a CW power level of 200 kW for use in microwave-generated plasma studies at the Oak Ridge National Laboratory. This device is of the gyroklystron type employing resonant cavities separated by drift spaces.

The work at NRL is concentrating on millimeter wavelengths and on addressing scientific and technical issues at the limits of the technology. Currently studies are underway with the near-term goal of demonstrating an efficient 200 kW amplifier at λ = 8 mm. The device configuration to be emphasized is the distributed traveling-wave amplifier similar to that shown in Fig. 1 because of its advantages in bandwidth and in handling high power. The field strengths encountered for a given power level will be considerably lower in a traveling wave device than in a device employing resonant cavities. Among the scientific issues to be addressed are the effect of self-fields of the electron beam and suppression of spurious mode generation in overmoded waveguide.

The advanced nonlinear theory of Sprangle and Drobot[6] has been adapted to cylindrical geometry[9] and used in obtaining a device design optimized for maximum efficiency. In this theory[6] it is shown that a threshold for the cyclotron maser instability exists at low energy (typically 10 - 20 keV transverse kinetic energy); at energies just above the threshold the process becomes saturated because the growth rate goes to zero as the transverse energy is depleted and approaches the threshold value. At higher energies, on the other hand, a quite different saturation mechanism occurs. As energy is removed from the electrons the cyclotron frequency increases until the gyrating electrons are trapped in a phase such that energy transfer ceases. Competition between the two mechanisms leads to a peak in efficiency as a function of beam transverse energy. The plot of efficiency vs transverse energy which was used in designing the 200 kW distributed amplifier at λ = 8 mm is whown in Fig. 2. Efficiency is seen to reach a peak value of 74% in these beam frame calculations. The corresponding efficiency of transferring beam energy to wave energy in the laboratory frame is 53% for the design value of $V_{\perp}/V_{\parallel}$ = 1.6.

An overall sketch of the traveling wave amplifier in which this design will be employed is shown in Fig. 3. In essence, it combines the magnetron injection gun which characterized the Soviet work with the input wave launcher and traveling wave interaction of the NRL intense beam amplifier. It is expected that this approach will eventually lead to devices which are characterized by the megawatt peak power levels of Table 1 combined with the high efficiencies of Table 2.

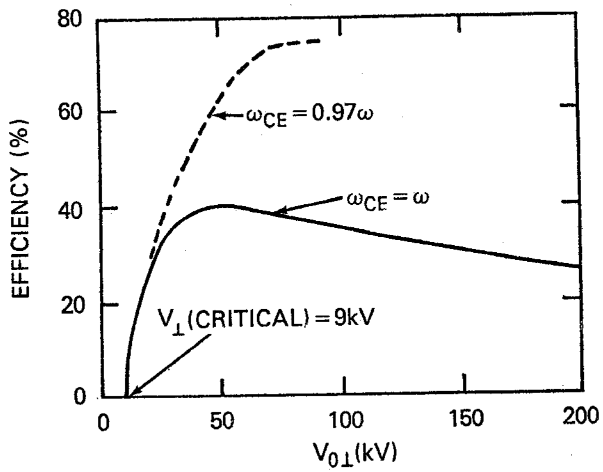

Fig. 2 - Calculated efficiency of cyclotron maser amplifier vs initial transverse electron energy, for beam current of 10 amps (from calculations based on theory in Ref. 6). Solid curve: cyclotron frequency = input wave frequency (TE_{01} mode); dashed curve: cyclotron frequency detuned 3% by reducing magnetic field. The calculations shown here have been used to design an efficient 35 GHz distributed amplifier at the 200 kW level.

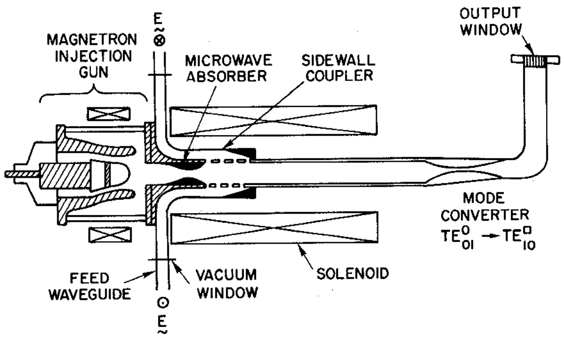

Fig. 3 - Sketch of the planned NRL gyro-traveling wave amplifier (TE^{o}_{01} mode, 35 GHz, operating at the fundamental of the cyclotron frequency). The solenoid is of the superconducting type.

Lastly, it should be noted that a superconducting magnet is being employed in the 8 mm device of Fig. 3. This will allow for future experiments at higher frequency. Preliminary design is in progress for a cyclotron maser which would generate tens of kilowatts at $\lambda = 3$ mm at the fundamental of the cyclotron frequency and kilowatts at $\lambda = 1$ mm at the 3rd cyclotron harmonic.

Beam-Wave Scattering Mechanisms

A second class of microwave sources involving pulsed technology is related to coherent backscattering of electromagnetic radiation from intense, relativistic-electron beams. These experiments are illustrated in Fig. 4. They fall into two types, mirror-like scattering from the rapidly rising front edge of the beam and stimulated scattering from induced electron density oscillations in the body of the electron beam.

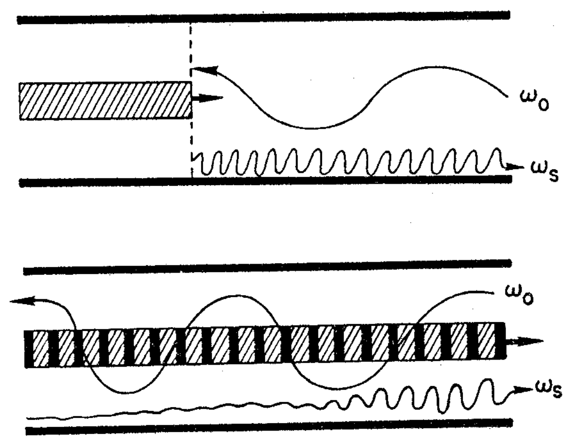

Fig. 4 - Two types of backscattering between an input wave ω_o and a counterstreaming intense relativistic electron beam, in a smooth cylindrical pipe. Upper illustration: scattering from rapidly rising front edge of beam; Lower: scattering from induced density oscillations in the body of the beam.

In both methods, a Doppler shift occurs, giving a strong upshift in frequency. The frequency of the backscattered wave, ω_s, is related to the frequency of the incident wave, ω_i, by the relationship $\omega_s = (1 + \beta)^2 \gamma^2 \omega_i$, where β and γ are the normalized velocity and normalized total energy of the electrons, respectively, i.e., $\beta = v/c$ and $\gamma = 1 + (T/mc^2) = (1 - \beta^2)^{-1/2}$. Here T is the electron kinetic energy. It should be appreciated that the Doppler shift can be large; for example, with 2 MeV electrons $\gamma \approx 5$ and $\beta \approx 1$ so that $\omega_s \approx 100\ \omega_i$ and an incident wave with a wavelength of 3 cm would yield a backscattered wave at 300 μm. Moreover, the output wavelength is adjustable by changing either ω_i or the electron energy. Thus devices based on coherent scattering promise to provide continuously-tunable, coherent sources at submillimeter wavelengths where no such sources are presently available. We propose to name such devices DOPPLERTRONS.

Unlike other common mechanisms for frequency conversion (e.g. harmonic generation in nonlinear components, or submillimeter generation in optically-pumped molecular lasers) the Dopplertrons promise energy and power gain. The energy of the backscattered output wave, W_s, is related to the energy of the input wave, W_i, by $W_s = (1 + \beta)^2 \gamma^2 R W_i$, where R is the reflectivity of the beam (i.e. the fraction of incident photons which result in backscattered photons). Clearly when the reflectivity approaches unity energy gain may be achieved that is almost as large as the Doppler frequency shift. Moreover, in the beam-front scattering version of the Dopplertron, relativistic time compression also occurs and thus the power gain will be larger than the energy gain by an additional factor of $(1 + \beta)^2 \gamma^2$.

The interesting feature of e.m. wave interaction with a reflector moving at relativistic speeds was first recognized by Albert Einstein in 1905.[10] In 1952, Landecker[11] described how the front of a magnetized relativistic electron beam could provide such a relativistic reflector. However, an experimental demonstration of beam front scattering was not made until 1976. A group at NRL demonstrated the conversion of a 3 cm incident wave into a 1 cm output wave with output power being twice as large as incident power.[12] In more recent studies at NRL,[13] the velocity of the beam-front electrons has been increased by steepening the rise time of the accelerating voltage pulse. This has resulted in a demonstration of converting a 3 cm incident wave into a 6 mm output wave with power in the output wave exceeding incident power by more than an order of magnitude. Moreover, in these recent experiments energy gain was achieved as well as power gain.

The beam front scattering process thus appears to be attractive for producing very high-power, high frequency pulses. However, it has a feature which may be a drawback in many practical situations: the output pulses produced are very short in duration. The scattering only occurs for the time it takes the beam front to propagate through the limited length of the interaction region, L, and in addition there is a relativistic time compression. Thus the duration of the output pulse is only $L/(v(1 + \beta)^2 \gamma^2)$, typically on the order of one nanosecond.

The second type of scattering, stimulated scattering from induced density fluctuations in the body of the electron beam, is not characterized by short output pulses, and can in fact produce an output pulse as long-lasting as the electron current pulse. This scattering process involves an instability in which the pondermotive force (radiation pressure force) generated by interaction between the incident and scattered e.m. waves modulates the beam electron density; this modulation in turn produces stronger scattering. The growth of the instability depends on the strength of the incident pump wave, and for e-folding lengths on the order of centimeters, one normally requires pump wave power at a level > 10 MW/cm^2.

The production of submillimeter radiation by stimulated scattering of a microwave signal from a relativistic electron beam was first proposed by Pantell.[14] Subsequent theoretical analyses included the effect of boundaries,[15] of an external magnetic field,[16,17] and of collective plasma effects.[17,18] An initial experimental study at NRL has used an incident 2 cm wave at a power of $\sim$ 100 MW to yield a 1 MW scattered wave at 400 μm.[19]

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