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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER HDL-TM-78-20	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) The Generation of High-Power Microwave Radiation from Intense Relativistic Electron Beams		5. TYPE OF REPORT & PERIOD COVERED Technical Memorandum
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) R. Alan Kehs Alan Bromborsky		8. CONTRACT OR GRANT NUMBER(s) DA: 1L161101A91A
9. PERFORMING ORGANIZATION NAME AND ADDRESS Harry Diamond Laboratories 2800 Powder Mill Road Adelphi, MD 20783		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Program Ele: 6.11.01.A
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Materiel Development and Readiness Command Alexandria, VA 22333		12. REPORT DATE November 1978
		13. NUMBER OF PAGES 25
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

DRCMS Code: 611101.91A0011
HDL Project No: A10726

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Microwave generation
Relativistic electron beams

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report provides a basis for evaluating the current and near-future development of relativistic-electron-beam (REB) technology for the generation of microwave radiation. Magnetrons, gyrotrons, and Raman scattering are examined in some detail and references are cited for several other conversion schemes. The status of repetitively pulsed REB generation is then reviewed

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20. Abstract (Cont'd)

and two hypothetical systems are constructed from the conversion schemes and generators that were considered earlier. Finally, some of the advantages (such as high power and compact size) and disadvantages (such as unproven technology) are summarized.

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1. INTRODUCTION

This report provides a preliminary basis for evaluating the feasibility of relativistic-electron-beam (REB) generated microwaves (ref 25, 30);* it examines the most important schemes for converting electron-beam energy to microwave and near-millimeter radiation. The current state of electron-beam generators is reviewed with an emphasis on small repetitively pulsed machines that would be suitable for Army use. Finally, two scenarios are constructed in which current and projected hardware are combined to form REB-driven microwave-radiation sources.

2. ELECTRON-BEAM MICROWAVE GENERATION

Although most of the current research effort is directed towards producing near-millimeter and submillimeter radiation, many devices operate in the S and X band regions where peak powers up to 4 GW have been observed (ref 42, 5). Figure 1 shows the peak power and frequency for several different schemes for converting electron-beam to microwave radiation, illustrating the wide range of operating regimes. The two high-power points, marked M, represent the results of relativistic magnetron experiments (ref 42, 5). The best high power at high frequency results have been obtained with gyrotron-type configurations, labelled G (ref 32). The next group of devices (labelled R) employ stimulated Raman scattering (ref 10, 38) to generate microwaves. The final points, labelled C (ref 53, 54), represent a new area of study: stimulated Cerenkov radiation. All these schemes employ foilless diode geometries and would conceivably make reasonable repeatable microwave sources. The relativistic magnetron, stimulated Raman scattering, and gyrotron processes are described in more detail in this report.

**Because this report is a literature survey, literature citations (given in parentheses) are listed in the Selected Bibliography (p 17), rather than on the pages where cited.*

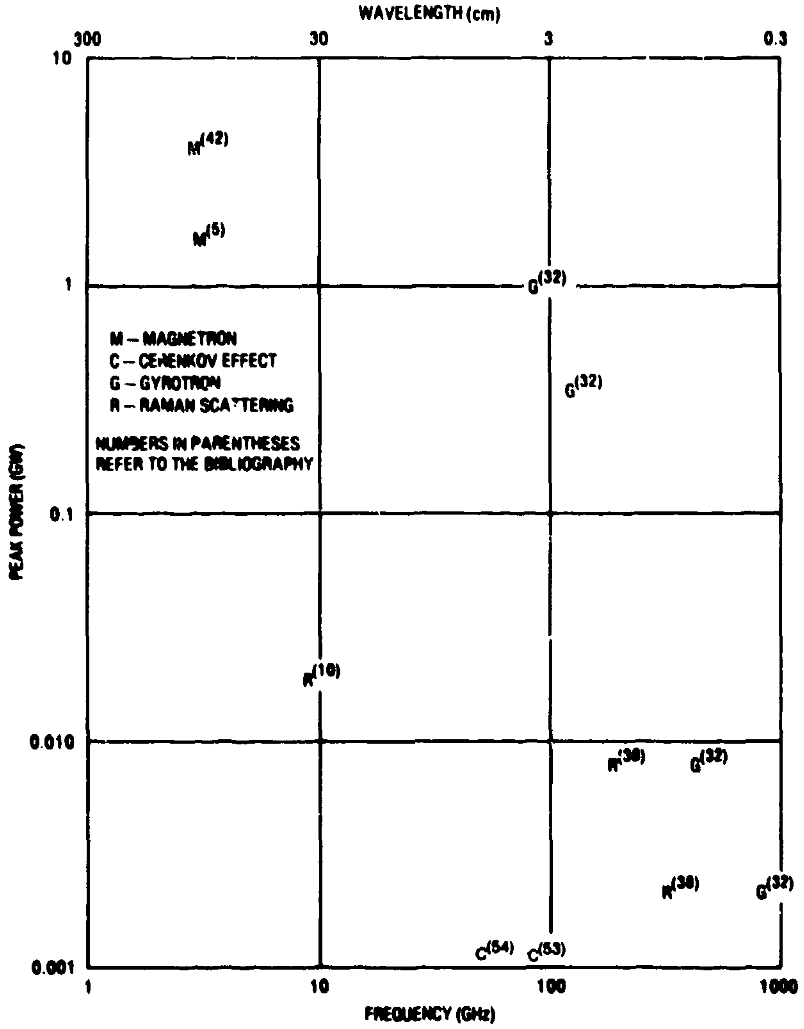

Figure 1. Peak power and frequency for several different electron beams.

2.1 Relativistic Magnetron

The relativistic magnetron is a high-voltage version of the simple classical magnetron (ref 13) that has been in use for many years. Figure 2 is schematic of the device used by Bekefi and Orzechowski (ref 5). The anode block (inner radius of 2.1 cm) has six vane-type resonators designed to oscillate at 3.0 GHz. Each resonator is 7.2 cm long. One of the resonators is provided with a slot through which the radiant energy is coupled into a microwave horn. The coaxial cathode is a graphite cylinder 4.8 cm in radius. It is connected via a steel shank to a Nereus (ref 43) pulse line. The entire system, including the transmitting horn, is pumped to pressures less than 10^{-4} torr. The axial magnetic field acting on the diode is generated by two solenoids mounted in an approximate Helmholtz-pair configuration.

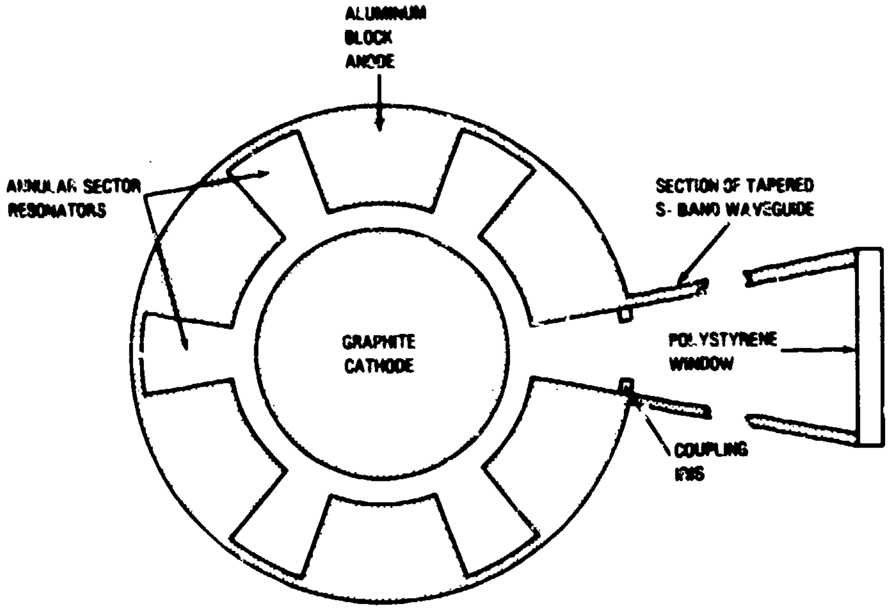

Figure 2. Magnetron diode.

Typical operating parameters for this system are ~12 kA of cathode current, an accelerating potential of ~ 360 kV, and an 8-kG axial magnetic field. Linearly polarized microwaves of 30-ns duration with a power level of 1.7 GW are produced. This represents a conversion efficiency of electron energy into microwave energy of about 35 percent. Work is under way at the Naval Research Laboratory (NRL) to increase this efficiency still further.

2.2 Stimulated Raman Scattering

During the last few years investigators have observed high-powered millimeter and submillimeter radiation from intense REB's undergoing stimulated Raman scattering (ref 19, 26, 28, 37, 38, 49.) In this coherent interaction, a low-frequency electromagnetic pump wave is backscattered from an REB to yield radiation whose frequency is much larger than that of the pump wave (ref 52).

Presently, there are two methods of providing an adequate pump wave: (1) by generating an electromagnetic wave to serve as the pump (ref 28) and (2) by propagating the electron beam through a spatially rippled magnetic field (ref 19, 38). Two zero frequency pumped (method two) Raman scattering experiments are considered: (1) an experiment employing a 1.4-cm period rippled magnetic field (ref 19) and (2) one using a 6-mm pitched helical undulator (ref 38). For the 1.4-cm period experiment (shown in fig. 3), the drift tube is a coaxial waveguide with alternating brass and iron rings internally loaded in the center conductor. The electron-beam parameters are 750 kV and 10 kA, and power levels of 1 to 5 MW are measured at 7-mm wavelengths. In the helical configuration, the beam propagates in a smooth iron tube with a deep-grooved helical screw of 6-mm pitch maintained in the outer wall. In this case, the beam parameters are 860 kV and 12 kA. Power levels of 6 to 8 MW are measured at 2 mm and 0.1 to 1.0 MW at 1 mm. In both cases, the power levels depend on the magnetic field which is varied from 6 to 12 kG.

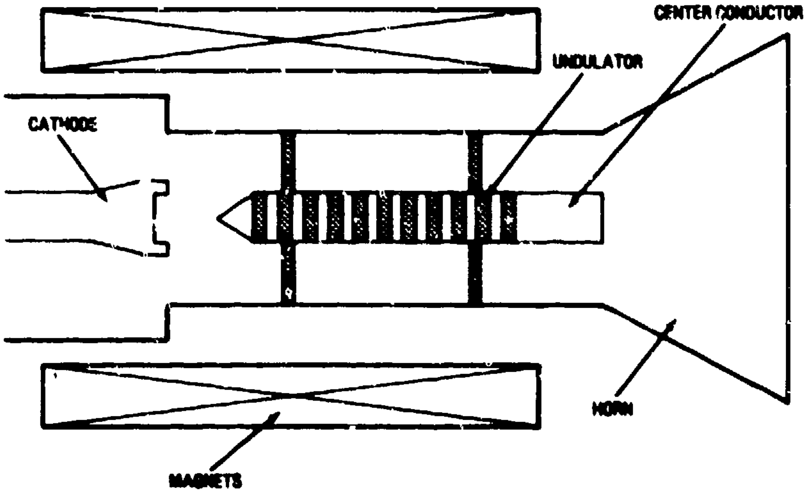

Figure 3. Typical Raman scattering experiment.

2.3 Gyrotron

Figure 4 shows the most popular configuration of the gyrotron (ref 17, 22, 57) (or electron cyclotron maser), namely, the axisymmetric gyrotron. The symmetry originates with the solenoid creating the magnetic field. Because of this symmetry, a cathode with a large emitting surface can produce an intense flow of electrons with rather small velocity dispersion. The flow undergoes compression by the magnetic field which increases in the direction from the cathode to the interaction space. The compression section represents a reversed magnetic mirror (shown in fig. 4) where the initial cathode orbital velocity of electrons (ref 38) grows according to the adiabatic invariance of magnetic moment. Here the orbital energy is drawn from that of the longitudinal motion and from the accelerating electrostatic field. In the interaction space, the electrons are guided by quasi-uniform magnetic fields. Escaping it, they enter the region of decreasing field (decompression section) and then settle on the surface of the collector.

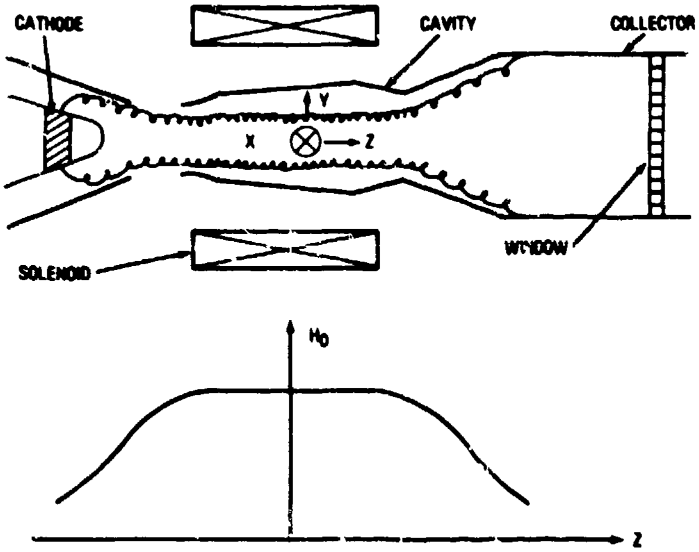

Figure 4. Common gyrotron arrangement.

In the interaction region, where the electron velocity is almost entirely transverse to the magnetic field, phase bunching can occur because of the relativistic mass change of the electrons (ref 23). Electrons absorbing radiation become massive and slip back in phase while electrons emitting radiation become less massive and advance in phase. This phase bunching of gyrating electrons causes the coherence of the measured radiation. The ultimate phase distribution favors emission over absorption, thus enhancing the intensity of the wave. Some experimental results are given in table I.

TABLE I. PEAK POWER LEVELS FROM CYCLOTRON MASERS (GYROTRONS) DRIVEN BY INTENSE REB.

Wavelength (cm)	Peak microwave power (MW)	Accelerating voltage (MV)	Diode current (kA)
4	900	3.3	80
2	350	2.6	40
0.8	8	0.6	15
0.4	2	0.6	15

2.4 Other Schemes

The generation of coherent Cerenkov radiation has been observed by several researchers (ref 9, 34), including ones at Dartmouth College and Columbia University (ref 54, 53). In their experiments, they used a modest 0.5-MeV, 10-kA electron beam with a foilless diode to generate 1 MW of microwave power at frequencies from 35 to 75 GHz (4 to 10 mm).

Intense microwave emission has also been observed during reflex triode operation at the Harry Diamond Laboratories (ref 7) and at NRL (ref 36) where 10 and 90 MW were measured in K_a and X microwave frequency bands.

Athough there are many more schemes that have not been discussed (ref 4, 8, 14, 15, 27, 29, 33, 35, 44, 50, 51, 56) it should be clear that intense REB's can be used to produce large amounts of microwave power at a very wide range of frequencies.

3. ELECTRON-BEAM GENERATORS

Capabilities for producing intense REB's (ref 21) have increased dramatically over the last several years. Although most of the industry's attention has been devoted to the super-high-power generators like the AURORA (10 MeV, 1 MA) (ref 6) and the PROTO II (1.5 MeV, 4.5 MA) (ref 39) facilities, a great deal of work has been done on improving the reliability, reproducibility, and repetition rate of the smaller (0.25 to 2 MeV, 5 to 30 kA) machines. A sampling of some of these electron-beam machines is listed in tables II and III. Two of these machines are discussed in more detail.

TABLE II. SAMPLING OF SOVIET REPETITIVELY PULSED REB MACHINES

Machine	Year	V_{max} (KV)	I_{max} (A)	Pulse length (μs)	PRF[a] (Hz)	P_{avg} (KW)	P_{max} (MW)	Reference
ELITA-500	1971	500	1.5	5	300	1	0.7	1
ELITA-1	1971	1000	15	4	300	8	10	
ELITA-1.3	1971	1500	100	0.05-3	100	2	150	
ELITA-3	1971	3000	40	10	300	20	100	
ELT1	1971	1300	0.07	6000	50	15	0.09	
ELT2	1971	1800	0.12	6000	50	25	0.215	
PRT	1971	1200	0.08	5000	50	10	0.295	
TEUS-15	1971	1200	0.125	?	?	150	?	
RIUS-5	1971	5000	30000	0.04	0.005	(0.03)	150000	
ELT 1.5	1967	1500	20	?	50	?	30000	2
ELT 2.5	1967	2500	?	?	50	?	?	
ELIT 1	1967	1000	100	0.06	50	3	100	
ELIT 3	1967	3000	?	?	100	?	?	
--[c]	1976	1400	50	0.03-1	100	5	(70)	3
--	1976	1200	150	0.2	50	0.45	180	
--	1976	250	4000	0.015	?	?	?	PORTABLE
	1976	2300	?	1000	?	?		

[a] *Pulse repetition frequency*

[b] *numbers in parentheses are inferred*

[c] *-- = machines not named*

TABLE III. SAMPLING OF U.S. REPETITIVELY PULSED REB MACHINES

Machine[a]	Year	V_{max} (kV)	I_{max} (kA)	Pulse length (μs)	PRF (Hz)	P_{avg} (kW)	P_{max} (MW)	Built by	Reference
--[b]	1973	125	20	0.04	1/60	?	(2.5)[c]	Berkeley	41
--	1976	40?	?	10	125	500	?	Maxwell	12 (Burst 30 to 75 s)
--	1976	240	1000	25	10	(6000)	(240000)	Maxwell	20 (Burst 60 s)
--	1976	75	60	?	10	?	(4500)	Sandia	55
CCEBL	1976	350	3	5	50	(700)	(2800)	Army	16
--	1975	6	6	20	300	62.5	(36)	Westinghouse	24
Modified Trace	1978	350	30	0.03	100	30	(10)	Sandia	47
--	1976	100	?	?	1	?	?	Maxwell	40 from modules
--	1973	35	0.015	2.5	44000	(60)	(0.525)	SLAC[d]	18
TRADEX	1973	130	0.14	3-128	(1000)	(0.072)	(18)	RCA	11 Burst
--	1973	78	(0.04)	16-32-55	75-210-300	22.6	3.27	Westinghouse	31
--	1973	120	(0.083)	7.5	300	20	10	Westinghouse	31
--	1973	185	0.16	2.5	360	65	30	SLAC	48

[a] *For additional machines, see table I in reference 54.*

[b] *-- = machines not named*

[c] *Numbers in parentheses are inferred.*

[d] *SLAC = Stanford Linear Accelerator*

3.1 Nereus Relativistic Electron-Beam Generator

Nereus machines (ref 43) are used as the electron-beam source in several of the microwave-generating schemes discussed in the preceding sections. Although they can easily be modified (and some have been) to produce higher voltages with less current, the basic machine delivers a single 80-kA pulse 250 to 400 keV with a pulse length of 30 ns.

The Nereus generator is an example of "classic" electron-beam machine design. An oil-insulated Marx Generator is used to charge a water-dielectric transmission line. This transmission line is then discharged by a polyethylene switch, past a prepulse resistor, through a vacuum diode. The entire facility could easily be placed on the back of a small flatbed truck.

3.2 High-Repetition-Rate Trace Machine

The original TRACE electron-beam generator (ref 45) is a simple compact machine in which a transformer is used to charge a Nereus pulse-forming line (PFL). This system is approximately 1.5 m long, 0.6 m wide, and 1.2 m high and includes all system components mounted on a roll-around platform except for the control panel and vacuum roughing pump. The system is designed to operate with up to 500 keV on the PFL and to generate a 100-kA, 30-ns electron beam.

Using this pulser as a starting point, a program to develop a series of repetitively pulsed generators has been undertaken at Sandia Laboratories (ref 47) beginning with a pulser designed to deliver 350-keV, 300-J, 100-ns pulses at a continuous rate of 100 per second. From these specifications, the output current is 8.6 kA and the generator impedance is 41 ohms. The machine that was actually built (ref 46) has a shorter pulse length (30 ns) and a correspondingly high current (30 kA).

The working system (shown in fig. 5) consists of a low-voltage modulator section, a voltage step-up transformer, a PFL, a high-voltage switch, and a load resistor or diode. The modulator converts dc power at 10 kV to primary pulsed power at 20 kV by resonant charging a 1.5-μF capacitor from a 14.5-μF capacitor. When the 1.5-μF capacitor is subsequently discharged through the primary of the voltage step-up transformer, the PFL is charged to 700 kV. Near the peak of the charge cycle, the output switch closes and energizes the load. At full voltage and 100 pulses per second, the average power output of the system is 30 kW.

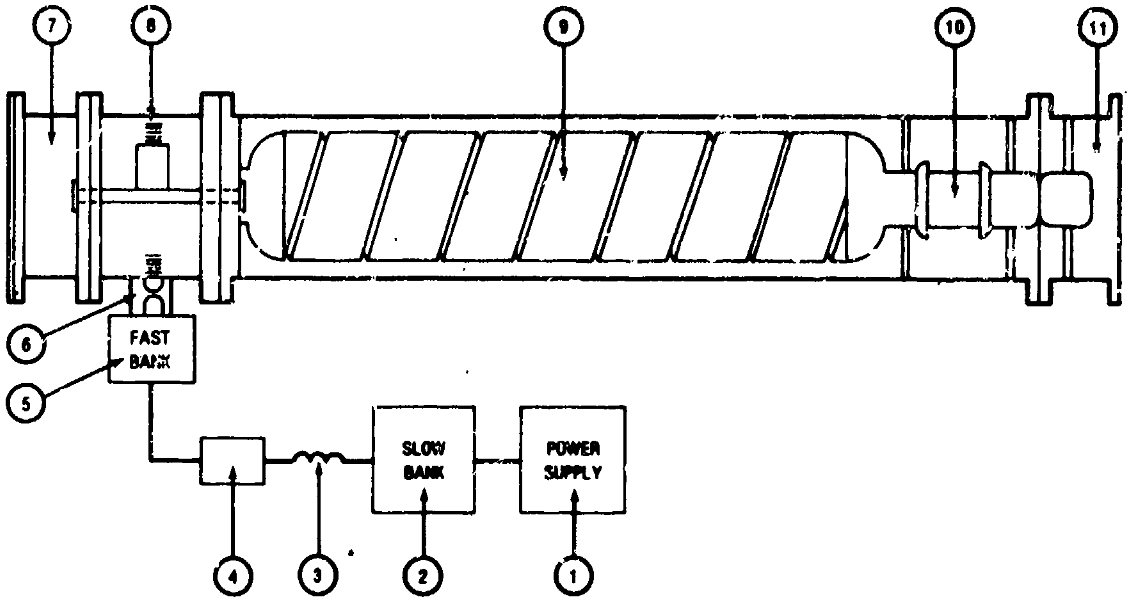

Figure 5. Pulser assembly including (1) 120-kV power supply, (2) primary storage capacitor (14 μF), (3) charging inductor (300 μH), (4) slow transfer interstage switch, (5) secondary storage capacitor (1.5 μF), (6) high current switch, (7) transformer high-voltage shield (oil filled), (8) transformer, windings, and central high-voltage bus shown schematically, (9) helical pulse forming line, (10) high-voltage output switch, and (11) cylindrical salt water load resistor.

The complete pulser system has undergone tests up to 100 pulses per second at 15-kW average power and 30 pulses per second at full voltage. A total of 2×10^6 shots was fired during the preliminary trials with individual runs of up to 1.5×10^5 shots. During these test runs, there were no major component failures or heat buildup problems.

3.3 Hypothetical Relativistic Electron-Beam Microwave Generating System

The relativistic magnetron described by Bekefi and Orzechowski (ref 5) was driven by an electron beam that delivered about 12 kA at 360 keV. Linearly polarized microwaves at powers of 1.7 GW were measured at 3 GHz; the efficiency of converting electron energy into microwave radiation was 35 percent. If this experiment were driven by the repetitive generator described in the previous section (with its 30-kA output), the peak microwave output should increase by a factor of 2 to 3 to yield about 5 GW per shot at a conservative repetition rate of 30 pulses per second. This would only correspond to about 5 kW of average radiated power, but this represents an impressive "first step" towards using and developing these techniques.

It should be noted that much work would need to be done if this hypothetical system were to constructed. The most important problem would be to determine whether REB could be operated repetitively.

The major effects to be analyzed and measured in determining the feasibility of interfacing a repetitive-pulse power supply and a super-high-power REB microwave source are (1) the thermal loading produced by electrons and ions hitting the anode and cathode of the microwave device, (2) the magnitude of plasma abrasion upon the anode and cathode, and (3) the effect of plasma formation on insulator flashover recovery time. Even at very low repetition rates (one shot every few minutes) where physics and engineering problems begin to disappear, the large bursts of generated energy must still be coupled into some sort of antenna.

Thus far, the evaluation of REB microwave-generation schemes has been conservative. Since no determination of physical limitations has been made, the potential of the merger of these two technologies should also be considered with cautious optimism. A program is under way at NRL and at the Massachusetts Institute of Technology to double the efficiency of the REB magnetron to about 70 percent, it is hoped. Also, the goal for the next generation of repetitively pulsed electron-beam machines at Sandia Laboratories is to exceed the first generation by a factor of ten. If this can be translated directly into microwave power at 70-percent efficiency, then the output would rise to nearly 100 GW per shot at 100 shots per second for an average power radiated of 100 kW. If these improvements do not require any gross increases in component size, the entire system would remain easily transportable. Of course, the above system represents a large amount of extrapolation, but repetitively pulsed electron-beam technology is in its infancy and it is impossible to predict how far and how fast the field will develop.

4. CONCLUSIONS

Many different ways of converting REB energy into radiated microwaves have been demonstrated in laboratories around the world. The frequency of the generated radiation varies from 1 to 100 GHz with power levels up to several gigawatts.

Although the super-high-power REB generators like AURORA and PROTO are unreliable and inconsistent--as were their predecessors--a new generation of REB machines has begun to fill in the gaps behind them. These "new" generators (like the Nereus and TRACE machines) are characterized by high efficiency, compact size, reliable operation, reproducible output, and widely varying output ranges. Microwave engineers who are interested in an ability to produce exceptionally high peak powers and increasingly higher average powers should not overlook the attractive possibilities of REB microwave generation.

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