Conf-900711--15

INVITED PAPER, presented at BEAMS '90, Novosibirsk, USSR, July 2-5, 1990

A PROGRAM OF HIGH POWER MICROWAVE SOURCE RESEARCH AND DEVELOPMENT FROM 8 GHz TO 600 GHz

V.L. Granatstein, T.M. Antonsen, Jr., S. Bidwell, J. Booske, Y. Carmel, W.W. Destler, R.A. Kehs, P.E. Latham, B. Levush, W.R. Lou, I.D. Mayergoyz, K. Minami, and D.J. Radack

Laboratory for Plasma Research
University of Maryland
College Park, Maryland 20742 U.S.A.

CONF-9007111--15

FG

DE91 008320

Abstract

We review research results both on a plasma filled, backward wave oscillator (BWO), and on a free electron laser (FEL) driven by a sheet electron beam. Recently, it was demonstrated that a plasma filled BWO driven by an intense relativistic electron beam can generate hundreds of megawatts of microwave radiation at an unusually high efficiency of 40% compared with a typical efficiency of ~10% in a BWO without a background plasma. Furthermore, the enhanced efficiency can be maintained even for large electron beam currents approaching the vacuum space charge limiting current, and we anticipate this might hold even for larger current values. Theoretical studies and numerical simulations indicate that the enhanced efficiency as well as a lower value for the start oscillation current in the linear regime may be due to the finite length of the BWO circuit coupled with modification of the dispersion relation due to the background plasma. In the case of our FEL studies, we present designs for a 1 MW, CW, tapered FEL amplifier operating at frequencies of 280 GHz and 560 GHz. A short wiggler period ($\ell_w \sim$ 1 cm) is combined with a sheet beam of electrons having energy ~ 1 MeV. Depressed collector techniques would allow the main power supply rating to be reduced to ~200 kV. Efficient sheet beam transport (> 99%) has been demonstrated through 10 wiggler periods, and transport through 60 wiggler periods is currently under study. Finally, plans for a proof-of-principle tapered FEL amplifier experiment at 94 GHz are presented.

1 INTRODUCTION

A number of high power microwave generation experiments are in progress at the University of Maryland. These include the following:

(a) basic research studies on a large orbit fundamental mode (TE_{11}) gyrotron driven by a 2 MV intense electron beam, and producing 800 MW of radiation at a frequency of 660 MHz with 20% efficiency[1];

(b) basic research studies on a plasma filled, backward wave oscillator (BWO) driven by a 630 kV intense electron beam, and producing 400 MW of radiation at a frequency of 8.4 GHz with 40% efficiency[2,3];

(c) research and development of 10-20 GHz gyroklystron amplifiers with possible application to driving future electron-positron supercolliders[4]; the gyroklystron currently under study is driven by a 500 kV, 160 A electron beam with pulse duration of 1.5 μsec and repetitive pulsing capability. It is intended to produce microwave output pulses in the 25-50 MW power range at a frequency of 10 GHz; and

(d) research and development of CW free electron lasers operating near a wavelength of 1 mm and at a power level of 1-2 MW with possible application to heating of plasma in magnetic fusion research devices[5]; intense relativistic electron beams have been used to demonstrate stable, non-intercepting propagation of the required sheet electron beam and to prepare a proof-of-principle FEL amplifier demonstration at 94 GHz.

Project (a) is at a lower operating frequency than is covered by the present paper. Project (c) on the gyroklystron amplifiers is described in a separate paper at this conference.[6] Project (b) on the plasma-filled BWO is described in section 2 below, while project (d) on the CW near-millimeter FEL is described in section 3.

2 STUDIES OF HIGH POWER PLASMA FILLED BACKWARD WAVE OSCILLATORS

Relativistic backward wave oscillators (BWOs) and related devices like multiwave Cerenkov generators have proven to be efficient, high power (up to 15 GW) microwave sources in the centimeter and millimeter wave range, capable of radiating about 1 kJ of microwave energy in a single pulse.[7,8]

One approach to increasing the power generating capabilities of microwave devices is to introduce plasma into the device. In this way, very large electron beam currents (well above the vacuum space charge limit) may be propagated, resulting in extremely high power microwave generation. In this section, we report the results of experimental and theoretical studies of an 8.4 GHz BWO filled with a controlled plasma background (Fig. 1), powered by an intense electron beam at currents approaching the vacuum space charge limit.

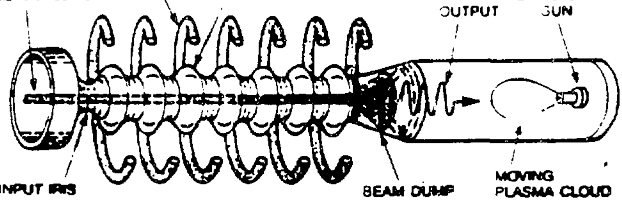

Figure 1: Schematic diagram of the plasma loaded BWO experiment

The experimental configuration used for these studies is shown in Fig. 1. A hollow relativistic electron beam of radius 0.8 cm and radial thickness 0.2 cm is injected into a BWO slow wave structure. The slow wave structure was designed to operate in the TM_{01} mode at a frequency of 8.4 GHz. The entire device was immersed in an axial magnetic field. Two current monitors, one located upstream of the anode plane to measure the injected current (called the diode current), and another located downstream to measure the current propagating into the slow wave structure (called the beam current) are employed. When the electron beam current injected into the structure is well below the space charge limit, total transmission is obtained. As the electron gun current is increased to a value approaching the space charge limit, only a fraction of the current (55%) actually propagates into the slow wave structure. In an attempt to drive the device at higher current, an independent hydrogen flashover plasma gun was used to inject plasma directly into the slow wave structure. The plasma gun generated a plasma cloud moving at an average velocity of about 5–10 cm/μsec and with a temperature of a few eV. It was found that the plasma allows injection of large current into the BWO, and about 90% of the gun current was successfully propagated through the structure as shown in Fig. 2.

2.1 Theory of Plasma Filled Relativistic BWO

As a first step in the development of a comprehensive theory of plasma loaded relativistic BWO, we have developed a linear and a nonlinear theory for a vacuum relativistic BWO of finite length.[10] The model takes into account the finite reflectivity of the electromagnetic waves at both the input and output of the slow wave structure. Figure 3 displays the normalized start oscillation current as a function of the normalized length $\kappa_0\mathcal{L}$ for combined power reflection coefficient of 0, 9% and 50%. The normalized length is defined as $\kappa_0\mathcal{L} = \mathcal{L}\omega/v_{z,0}$, where ω is the radiation

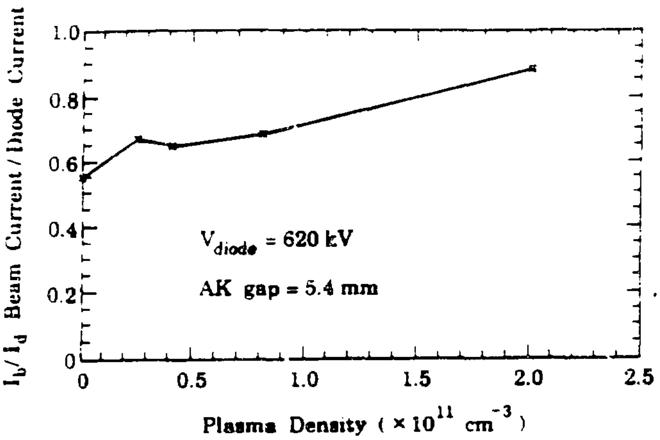

Figure 2: Beam current/diode current vs plasma density

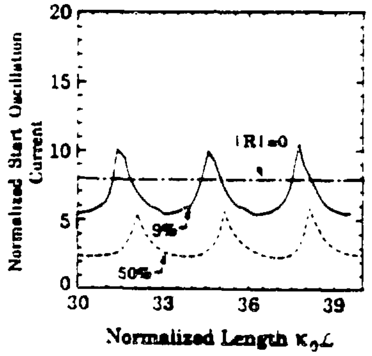

Figure 3: Normalized start oscillation current vs normalized length

frequency, $\mathcal{L}$ is the total length of the structure and $v_{z,0}$ is the injected beam velocity. From the plot, we observe that by varying the normalized length parameter by $\pi/2$, one can expect up to 200% variation in the start oscillation current. The presence of a low density plasma in the structure modifies the dispersion relation. It can be shown that the effective normalized length in the presence of low density plasma ($\omega_p \ll \omega$) has a form $\kappa_0\mathcal{L} + (1/2)\omega_p^2\mathcal{L}/(\kappa_0 v_{z,0}^2)$, where ω_p is the local plasma density. For the last term to be of order $\pi/2$, the ratio ω_p^2/ω_0^2 has to be of the order of $\pi/(\kappa_0\mathcal{L})$. In the case of our structure $\kappa_0\mathcal{L} \simeq 8\pi$, therefore $\omega_p^2/\omega_0^2 \simeq 0.13$. This indicates that the presence of low density plasma can strongly affect the start oscillation conditions in a relativistic BWO.

A recent PIC code simulation[11] indicates that modification of the dispersion relation by a low density plasma may also strongly affect the saturated BWO power level.

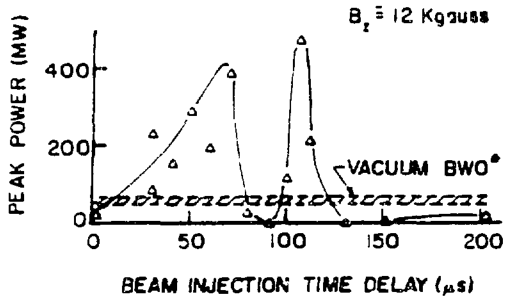

Figure 4: Peak microwave output power vs beam injection time delay

2.2 Enhanced Microwave Emission Via Plasma Injection

An enhancement of the microwave power generation efficiency was observed over a wide range of injected plasma densities. Variation of the firing delay between the plasma gun and the electron diode allowed one to control the plasma density inside the slow wave structure at the time of the electron beam passage. The microwave power output as a function of this firing delay is shown in Fig. 4. Microwave output rises to a peak of almost 600 MW, corresponding to an electron efficiency of about of 40%, compared with about 5% for the vacuum BWO. Under similar conditions this enhanced efficiency is maintained in a plasma BWO even for large beam currents approaching the vacuum space charge limit.

3 MILLIMETER-WAVE, HIGH-GAIN, HIGH-EFFICIENCY, TAPERED FEL AMPLIFIERS USING SHORT-PERIOD WIGGLERS AND SHEET ELECTRON BEAMS

Work is underway aimed at developing a cw, high power source of near millimeter-wave radiation. Specifically, our goal is to develop an FEL amplifier with a sheet electron beam and a short period tapered wiggler for use in electron cyclotron resonance heating (ECRH) of the plasma in proposed magnetic fusion experiments such as the Compact Ignition Tokamak (CIT). Requirements for the ECRH source[12] are pulses of ~10 secton duration, $\gtrsim$ 1 MW of average power, high system reliability and efficiency, at a frequency of ~ 300 GHz with additional interest at the second cyclotron harmonic at ~ 600 GHz.

Our previous work concentrated on an FEL oscillator system[2,3] meeting these needs. However, concerns for increased efficiencies and advances in superconducting

Table 1: Four designs for a CW, ~ 1 MW, tapered FEL amplifier at 280 GHz and 560 GHz, and parameters of a pulsed proof-of-principle experiment at 94 GHz.

Frequency (GHz)	280	280	560	560	94
V_{beam} (MV)	1.0	1.0	1.0	1.5	0.65
I_{beam} (A)	10	10	10	10	8.5
S_{beam} (cm^2)	.1 × 2	.1 × 2	.1 × 2	.1 × 2	.1 × 2
B_{w0} (kG)	7.0	10.0	10.0	10.0	7.0
B_{w_min} (kG)	2.0	2.0	2.0	2.0	2.0
ℓ_w (mm)	12.1	10.5	6.8	10.0	14.5
a_{w0}	0.79	0.98	0.63	0.93	0.95
S_{wg} (cm^2)	.60 × 3	.52 × 3	.37 × 3	50 × 3	.56 × 3
P_{sat} (MW)*	0.13	0.14	0.09	0.14	0.14
z_{sat} (m)	0.8	0.6	0.6	0.9	0.6
η_{taper} (%) ($f_t \approx 0.7$)	12	17	9	15	18
L_{taper} (m)	1.2	1.3	1.0	2.3	0.7
P_{out} (MW)	1.2	1.7	0.9	2.1	1.0
η_{tot} (%) ($\eta_r = 0.7$)	31	41	24	36	
η_{tot} (%) ($\eta_r = 0.8$)	41	51	32	46	
ϕ_{LV} (kV) ($\eta_r = 0.7$)	171	243	129	300	
ϕ_{LV} (kV) ($\eta_r = 0.8$)	150	213	113	262	

* 1 KW input for designs at 280 and 560 GHz; 500 kW input at 94 GHz.

The proposed wiggler magnet will consist of two sections, a uniform wiggler parameter section followed by a tapered section. The uniform wiggler section will provide exponential gain and will take the signal to saturation. Saturated power values (P_{sat}) as well as lengths for the uniform section (z_{sat}) can be found in Table 1. At the saturation distance the wiggler magnet will begin tapering to boost powers to levels of interest and to increase intrinsic efficiency. For a linear taper the intrinsic efficiency is given by

$$\eta_{taper} \approx \frac{\Delta\gamma}{\gamma_0 - 1}\,\frac{\overline{\beta}_z}{\beta_0} f_t$$

where $\Delta\gamma$ is the change in γ over the tapered region and

$$\Delta\gamma = \overline{\gamma}_z \left[\sqrt{1 + \frac{1}{2}a_{w0}^2} - \sqrt{1 + \frac{1}{2}a_{wt}^2}\right]$$

and γ is the relativistic energy parameter, β is the normalized velocity, f_t is the trapped beam fraction, and a_{w_0} and a_{w_L} correspond to the wiggler parameter at taper entrance and exit respectively. Note that efficiency is directly proportional to the trapped fraction. We have chosen a 70% trapped fraction which has been experimentally observed elsewhere.[16] Also note that high efficiencies require a significant change in the wiggler parameter from the entrance to the exit of the tapered region. For these designs, field tapering gives $B_{w,min} = 2$ kG at the end of the tapered length. Minimum field values are constrained by trapping and beam confinement considerations.

Through tapering, intrinsic efficiencies of between 15% and 20% are expected. These relatively large efficiencies favorably influence demands upon both electron beam power and, as will be discussed, spent beam energy recovery.

Lengths for the tapered region are typically over 1 m and, combined with the uniform section, the overall interaction length will be between 1.5 m and 3.0 m. These relatively long lengths have motivated our ongoing beam propagation work to be discussed in Section 3.2.

As an ECRH source, the amplifier must be efficient to keep costs low. The proposed energy recovery scheme utilizes a depressed collector in which the streaming spent beam is sorted and decelerated prio to collection. The overall efficiency for the amplifier system can be expressed as

$$\eta_{tot} = \frac{\eta_{taper}}{1 - \eta_r(1 - \eta_{taper})},$$

where η_r is the energy recovery efficiency realized by the depressed collector. Energy recovery efficiencies of 70% to 80% yield overall system efficiencies between 30% and 50%.

The amplifier will require two power supplies. One, a main power supply of 100-300 kV will provide the bulk of the beam current ($\sim$ 10 A). A second high voltage bias supply at $\gtrsim$ 1 MV will be required to handle less than $\sim$100 mA of stray current. Both power supplies are commercially available.

To drive the FEL amplifier, a cw input rf source at 300-600 GHz will be needed. The designs of Table 1 are based upon 1 kW of input power.

A logical first step toward developing this amplifier is to demonstrate sheet beam propagation through a wiggler with relevant parameters and length. In this regard, past and present beam propagation work is now discussed.

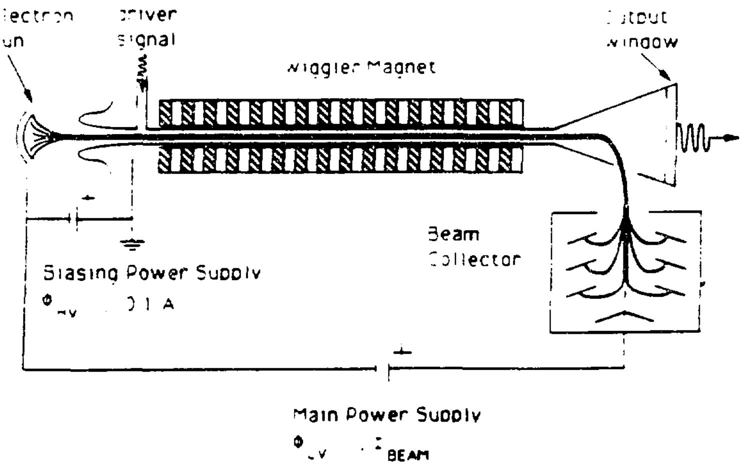

Figure 5: Schematic of the cw, 1 MW FEL amplifier.

wigglers (permitting access to the high-gain regime) have prompted our consideration of a tapered FEL amplifier.

3.1 Design of a cw 1 MW, Tapered FEL Amplifier

In this section we describe our approach to developing a cw, 1 MW source of radiation at 300-600 GHz. Specifically, our choice is a tapered, superconducting FEL amplifier, a schematic of which is illustrated in Fig. 5. Four corresponding designs are presented in Table 1. A high voltage ($\gtrsim$ 1 MV) thermionic Pierce-type electron gun will be used to generate the sheet electron beam. The sheet beam will have dimensions of 0.1 cm by 2.0 cm and will carry approximately 10 A of current. The gun will use a multi-electrode structure to electrostatically compress the beam. A 1.0 MV gun design obtained by using the EGUN code[14] indicates that most specifications (including emittance) can be met.[15]

The interaction region will consist of a superconducting, planar, electromagnet wiggler capable of supplying 10 kG fields on axis. Recent research indicates that fields approaching this value may be possible.[16,17] The intense fields are required to access the high gain regime of operation. Specifically, a value of wiggler parameter,

$$a_w = \frac{eB_w\ell_w}{2\pi mc^2},$$

near unity is desirable. Wiggler periods $\ell_w \sim 1$ cm combined with the large field (B_w) values give the desired value of a_w.

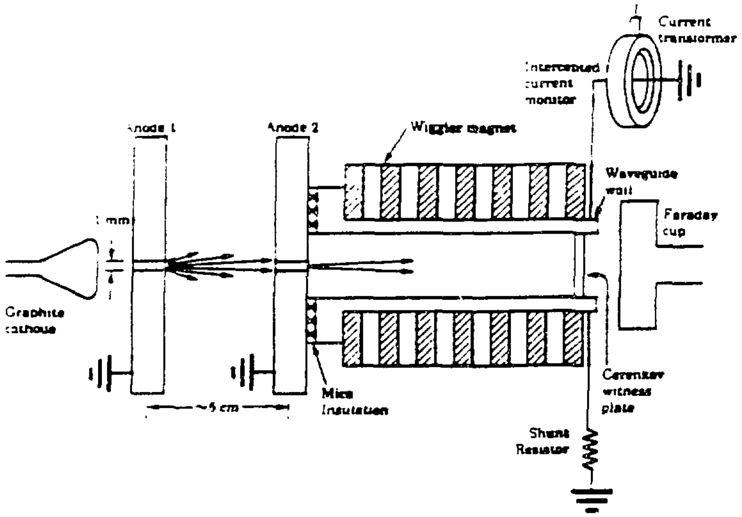

Figure 6: Experimental configuration for the ten-period sheet beam propagation experiments with the two aperturing anodes shown.

3.2 Sheet Beam Propagation Studies and a Proof-of-Principle Experiment

Sheet electron beams have some advantages over cylindrical beams. First, the beam current can be increased simply by increasing the wide transverse dimension of the sheet while keeping current density constant. Second, sheet beams are compatible with planar wiggler magnets. As magnetic fields fall off exponentially from the pole surfaces, high field strengths necessitate narrow pole gaps. A sheet beam with its narrow dimension fitting within the gap is an intuitive choice. Third, no axial magnetic field is necessary to maintain stable, confined sheet beam propagation. In fact, focusing is provided by the wiggler magnetic field gradient.

Much of our experimental effort to date has concentrated on studying sheet electron beam propagation.[19,20] The emphasis on propagation is warranted by concern for avoiding beam interception with resultant wall heating as well as concern for achieving high system efficiency.

Our past experimental work concentrated on propagation of a relativistic (0.5 - 1.0 MV) sheet beam with total currents between 1-100 A. These studies used a 1 cm period, ten period long wiggler providing fields of up to 2 kG on axis. The experimental configuration is illustrated in Fig. 6. A cold, field emission cathode produced the beam which becomes a sheet after passage through slits (1 mm × 36

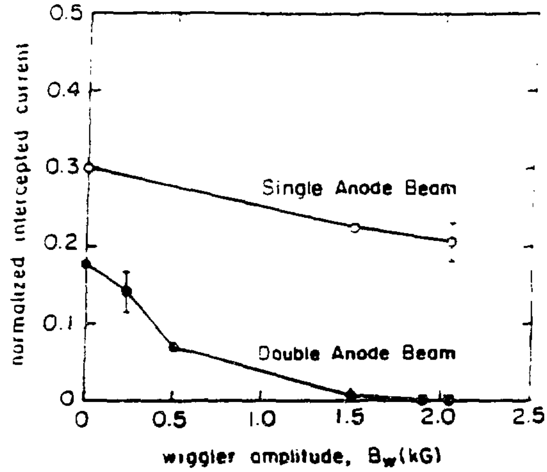

Figure 7: Normalized intercepted current as a function of wiggler field strength. Open circles represent the single anode configuration while closed circles are for the double anode.

mm) machined into the two anode plates. First experiments used one anode plate and it was found that as much as 20% of the injected beam current intercepted the waveguide, even with maximum wiggler field strength. Theoretical calculations indicate that both space charge spreading of the beam and beam ballistics account for the interception.[20]

When a second anode plate was added, the beam was allowed to expand by its own space charge within the drift region between the two plates and thereby reduce its current density. Further, by geometric considerations, the second plate improved the divergence angle of the beam. Under these conditions, intercepted current was reduced to well below a fraction of 1% of the injected 7.2 A of beam current.[20] Intercepted current as a function of wiggler field strength is plotted in Fig. 7 for the single and double anode configurations.

The results of the ten-period experiments are encouraging; however, interaction lengths for a tapered amplifier will approach 2 m. In an effort to study transport through longer lengths, a 60 cm long, 1 cm period experiment is underway.[21] The experiment employs a pulsed electromagnet wiggler of a double-layer, 20 period modular design. Three such modules will be used to attain the 60 cm of total length.

It is expected that in addition to space charge and beam ballistics, at these longer lengths wiggler field errors will play a role in wall interception. In addition, longer transport requires beam side focusing (focusing in the wide transverse dimension). The side focusing method of choice is an offset pole technique producing net dc fields on the sides. Used in conjunction with the transport experiment is an in-house numerical trajectory code simulating the influences of field errors and side focusing methods.[22]

Following successful demonstration of sheet beam propagation through the long interaction length, we will initiate an amplifier experiment with many parameters relevant to the ECRH device. This proof-of-principle (PoP) experiment is discussed below. The parameters in the PoP experiment are listed in the fifth column of Table 1. The electron beam will be produced by a 650 kV pulse line accelerator (75 ns flat top with $\lesssim$ 3% voltage ripple), and a double anode will be used to collimate the beam as in Fig. 6. The magnetic field will be pulsed. It should be noted that many of the eventual design goals may be achieved in this PoP experiment including $a_w \approx 1$ and $P_{out} = 1$ MW.

Acknowledgment

This work was supported in part by the U.S. Department of Energy, Office of Fusion Energy, and by the U.S. Department of Defense.

References

1. Destler, W.W. et al., J. Appl. Phys. 66, 4089 (1989).

2. Minami, K. et al., Appl. Phys. Lett. 53, 559 (1988).

3. Carmel, Y. et al., Phys. Rev. Lett. 62, 2389 (1989).

4. Granatstein, V.L. et al., IEEE Trans. Nucl. Sci. 32, 2957 (1985).

5. Granatstein, V.L. et al., Appl. Phys. Lett. 74, 643 (1985).

6. Lawson, W. et al., Proc. of the 8th Int. Conf. High-Power Particle Beams, Novosibirsk, July 2-5, 1990.

7. Bugaev, S.P. et al., Radiotech. Electr. 7, 1488 (1987).

8. Bugaev, S.P. et al., IEEE Trans. Plasma Sci., special issue on high power microwaves, June 1990 (to be published).

9. Levush, B. and Antonsen, T.M., Jr., Digest 1990 IEEE Int. Conf. Plasma Sci., May 21-23, 1990, Oakland, CA, p. 135.

10. Lin, A.T. and Chen, L., Phys. Rev. Lett. 63, 2808 (1989).

11. Marshall, T., Lebacqz, J., and Godlove, T., Department of Energy Report, DOE/ER-0366, April 1988.

12. Booske, J.H. et al., Nucl. Instr. Meths. Phys. Rev., A285 (1,2), 1989, 92.

13. Herrmannsfeldt, W.B., Rep. SLAC-226, Stanford Linear Accelerator Center, Nov. 1979.

14. Booske, J.H. et al., IEEE Trans. Plasma Sci., special issue on high power microwave generation, June 1990, to be published.

15. Sheffield, R.L. et al., Proc. 11th Int. Conf. on Free Electron Lasers (Naples, FL, 1989) p. 100.

16. Batchelor, K. et al., Proc. 11th Int. Conf. on Free Electron Lasers (Naples, FL, 1989) p. 116.

17. Orzechowski, T.J. et al., Phys. Rev. Lett. 57, 2172 (1986).

18. Booske, J.H. et al., J. Appl. Phys. 64, 6 (1988).

19. Radack, D.J. et al., Appl. Phys. Lett. 55, 2069 (1989).

20. Radack, D.J. et al., Digest 1990 IEEE Int. Conf. Plasma Sci., May 21-23, 1990, Oakland, CA, p. 196.

21. Bidwell, S.W. et al., Bull. Am. Phys. Soc., 35, 1026 (1990).