Efficient Electrostatic-Accelerator Free-Electron Masers for Atmospheric Power Beaming

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***Abstract*— The electrostatic-accelerator free-electron laser (EA–FEL) operating at mm wavelength is considered as a source for energy transfer through the atmosphere to a high altitude platform. The high average power and high efficiency attainable from appropriately designed EA–FEL make it a suitable candidate as an efficient source of mm-waves for power beaming from a ground station. Various aspects of the FEL as a high power oscillator (operating voltage, e-beam current, gain and efficiency) are reviewed; design tradeoffs are described. The study includes consideration of typical requirements of power beaming to a high altitude platform such as atmospheric absorption versus frequency and transmitting and receiving antenna requirements. A conceptual design of a compact, moderate voltage (0.5–3 MeV), high current (1–10 Amp) EA–FEM operating in the mm-wavelength band is presented as an efficient power source for space beaming. The FEM design parameters are presented based on analytical and numerical models. Expected performance parameters of an FEL (gain, energy conversion efficiency, average power) are discussed as related to the proposed application.**

I. Introduction

THE CONCEPT and schemes of microwave power transmission through the atmosphere were proposed and developed by Brown [1], [2]. In 1964, he successfully flew a small helicopter using microwave power beamed from a magnetron operating at 2.45 GHz [1], [2]. Modifications of these schemes based on high-power millimeter wave sources are under intensive consideration [3]. In this paper we shall address the problem of providing electric power to loitering high-altitude platforms requiring average power levels of 50 to 200 kW.

The radiation is transmitted through the atmosphere to a flying platform, where it is received and converted into dc electrical power by a rectifying receiving antenna (rectenna). Schematically this system is shown in Fig. 1 (which was reproduced from [2]).

Realization of this concept for microwave power beaming with practical antennas to an unmanned aerial vehicle (UAV) flying at an altitude of 20 km (this altitude is most fitting for commercial applications, such as communication [4]) becomes possible by use of millimeter waves for power beaming [5]. Utilizing suitable frequencies at millimeter waves for atmospheric beaming, the sizes of the rectenna and of the transmitting antenna become practical. For this application a new type of 35 GHz rectenna based on thin-film technology was designed [5], [6] providing a rather high rectenna conversion efficiency (of the order of 50%).

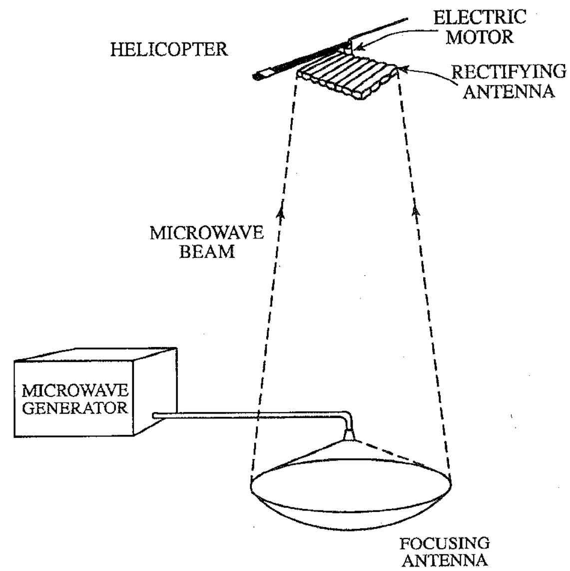

Fig. 1. Scheme of microwave power transmission through the atmosphere (reproduced from [2]).

In the selection of suitable microwave sources, one should consider the availability of high-power mm wave sources operating continuously at millimeter wavelengths. High-conversion efficiency, long operating life-time, and very high reliability are required from a suitable mm wave source for power beaming applications. Among the new very high power mm wave sources are gyrotrons and free-electron masers.

Recently developed gyrotrons can provide 0.5 MW power for 2 s at 110 GHz. Development programs call for 1 MW CW gyrotrons at 280 GHz [3]. Millimeter wave gyrotrons operating at 200 kW CW power are commercially available, and at the present time would probably be a preferable choice for moderate power transmission applications. There are, however, a number of limitations that should be pointed out as related to the use of gyrotrons and among these are the following.

1) The need to use super-conducting magnets in order to provide the high-magnetic fields that are required at mm wavelengths.

Manuscript received October 24, 1995; revised February 23, 1996. This work was supported in part by the Israeli Ministry of Energy and the Ministry of Science.

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Publisher Item Identifier S 0093-3813(96)05170-3.

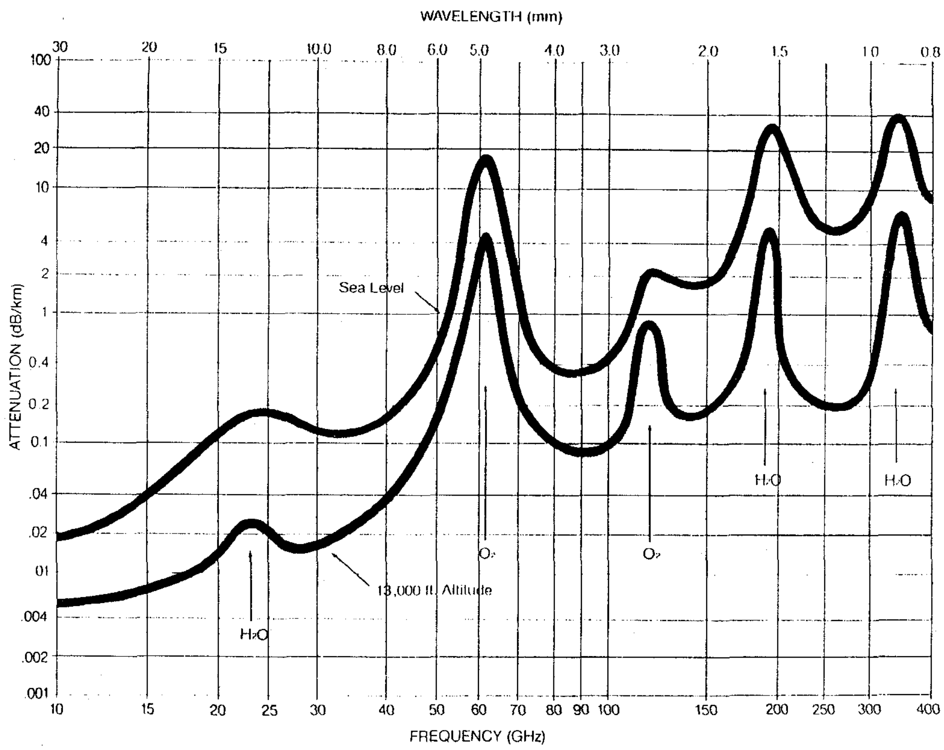


Fig. 2. Average atmospheric absorption of mm-waves.

2) The electron beam is generated and transported at very high currents, moderate voltage, and at considerable current densities at the cathode of a magnetron injection gun. These lead to possible lifetime degradation.
3) It is hard to realize an efficient depressed collector in a gyrotron, where a large transverse energy spread is generated in the spent electron beam.
4) After many years of development, gyrotrons are approaching the upper limit of their power and frequency capabilities; significant further improvement in their performances may be difficult.

It is thought that the newly evolving technology of EA–FEM may alleviate some of these limitations. A forerunner in the development of this high-power technology is a major European program at the FOM Institute for Plasma Physics, Netherlands, where a 1 MW CW FEM is being developed for operation in the 150 to 300 GHz band [7]. This FEM is designed for use as a source for plasma heating in tokamak fusion reactors. It utilizes a Pierce gun for generating a low emittance e-beam, and employs an efficient multistage depressed collector for energy recovery and efficiency enhancement. We propose the electrostatic-accelerator free electron maser as an appropriate future source of high-power mm-waves radiation for power beaming applications. The features of EA–FEM's characterized as very high average power devices with high-energy conversion efficiency were recognized [7]–[9] as fitting for various high-power applications, including plasma heating and power beaming. We wish to point out that such devices can operate also with quite compact accelerators (0.5–1 MeV voltage) at power levels sufficient for energy transmission applications.

TABLE I
ATMOSPHERIC POWER BEAMING TO 20 km

Frequency - f	35 GHz	94 GHz
Wavelength - λ	8.58 mm	3.19 mm
Atmospheric transmission	94%	79%
Diameter of rectenna - D_r	4 m	4 m
Diameter of transmitting antenna - D_{tr}	55 m	20 m
Rectenna conversion efficiency	50%	50%
Total transmission efficiency	35%	30%
Total transmitted power	200 kW	200 kW
Converted d.c. power	70 kW	60 kW

II. General Considerations

We consider energy beaming systems and in particular requirements of FEM's as mm-waves sources for such systems.

A. Operating Frequency

Inspection of atmospheric attenuation at millimeter waves (Fig. 2) reveals propagation windows near 35, 94, 130, and 220 GHz. We shall limit our considerations to the first two frequency bands (see Table I).

B. Antenna Dimensions

For efficient energy transmission through the atmosphere, diffraction is considered in the design of transmitting and receiving antennas. The dimensions of the antennas must be chosen so as to collect most of the transmitted power by the receiving antenna (rectenna). To reduce the rectenna size on

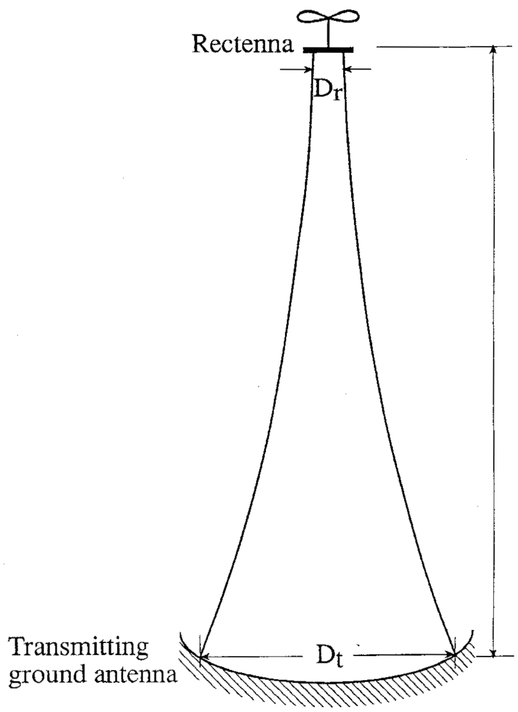


Fig. 3. Radiation beam focused on rectenna.

the UAV, the radiated beam is focused onto the rectenna as shown in Fig. 3. The diameter of the transmitting and receiving antennas are then related by the diffraction law

$$D_{tr} \approx \frac{4}{\pi} \frac{\lambda}{D_{\text{rect}}} d \tag{1}$$

where λ is the wavelength of radiation, D_{tr} and D_{rect} are the diameters of the transmitting antenna and of the rectenna, respectively, and d is the height of the platform. For example, with a circular rectenna of diameter of 4 m installed in the UAV at $d = 20$ km, the transmitting antenna becomes $D_{tr} = 55$ m (for 35 GHz) and $D_{tr} = 20$ m (for 94 GHz).

The transmitting antenna can be a single large dish, fed by a powerful source, or an antenna phased array, composed of a number of small radiating elements, fed by phase-locked sources [3].

C. Output Power

The required microwave source power may be estimated from the parameters of the power beaming system: the required dc power at the UAV, the rectenna and transmitting antenna sizes, the rectenna efficiency, and the atmospheric losses. Assume, for example, that the necessary dc power at the UAV is 50 kW. For a conversion efficiency of the mm-wave rectenna of about 50% [5], [6], and an incident power density on the rectenna of 1 W/cm^2 (this limitation is due to cooling conditions at high altitudes considered in [5]), we obtain a minimal rectenna diameter of $D_{\text{rect}} = 4$ m. Because of the high cost of the rectenna per unit area and a desire to reduce the airborne load this minimal dimension is chosen as a design parameter. This allows us to determine [from (1)] the diameter of the transmitting antenna. Considering all the factors of power transmission loss: the atmospheric attenuation, antennas transmission efficiency, and rectenna conversion efficiency, we obtain an overall transmission efficiency of 35% at $f = 35$ GHz, and of 30% at $f = 94$ GHz. Table I summarizes the estimated parameters of a power beaming system. Thus, an FEM having an average output power of 200 kW can provide the required dc power to a UAV platform. Such an FEM mm wave output power can be achieved by use of appropriate operating voltage, e-beam current, wiggler parameters, and out-coupling from the resonator (design of such FEM's is described in Section IV).

D. Source Efficiency

The FEM efficiency must be high. High efficiency decreases the required input power and also the severe heat dissipation problems which exists in high average power devices. The overall efficiency is determined by the extraction efficiency of microwave energy from the e-beam and by the efficiency of kinetic energy recovery of the spent e-beam. Efficiencies of the order of 50% can be achieved in EA–FEM's utilizing a multistage depressed collector system [10]–[13].

E. Spectral Stability

The requirement of spectral stability of the mm-wave source is determined mostly by the bandwidth of efficient rectenna operation. The rectenna (see [6]) employs solid-state GaAs diodes, microstrip resonant dipole antennas, low pass filters, and a ground plane, placed at $\sim\lambda/4$ from the diodes plane, as a matching element. Such a rectenna design provides a rectified power output which is sensitive to frequency deviations from optimum frequency f_0. Frequency deviations larger than permitted lead to appreciable diode and dipole antenna mismatch and to a drop in rectenna conversion efficiency.

Typically, EA–FEM's are characterized by a spectral purity much better than that required as mentioned above meaning that the e-beam transport and voltage stability are such as to avoid radiation frequency shifts.

F. Continuous and Reliable Operation.

For long life, continuous operation of a sky platform at constant height, a mm-wave source operating continuously is required. The electrostatic-accelerator FEM employing a depressed collector [10]–[13] allows for such operation. The EA–FEM enables high e-beam transport efficiency and thus avoids accelerating voltage droop (which would lead to oscillation stoppage). It is robust, uses proven technology, and its lifetime is determined mainly by the cathode lifetime. Based on the experience of conventional microwave tubes, lifetimes in excess of 10 000 h should be expected.

III. Electrostatic Accelerator FEL's

Most FEL facilities in the world are based on RF linacs, which produce short duration e-beam pulses, few FEL's utilize electrostatic accelerators, which enable continuous wave or quasi-CW (long pulse) operation. Electrostatic accelerator

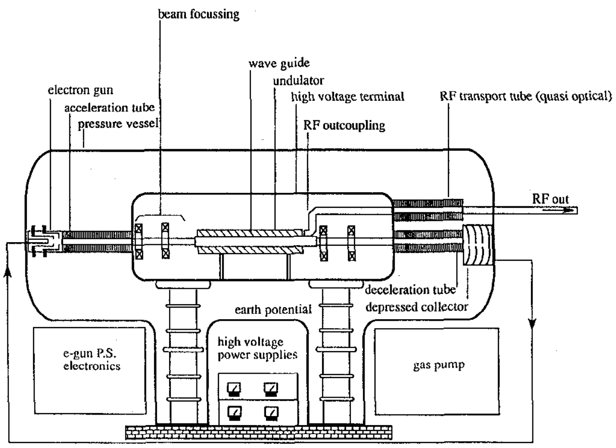


Fig. 4. Conceptual scale design of a compact EA–FEM (after [7]).

FEL's are, therefore, characterized by the capability of high average power generation, high-energy conversion efficiency, and high-spectral purity.

Energy recovery in electrostatic accelerator FEL's is intrinsically easier than in FEL's using RF accelerators. Excellent energy retrieval efficiency in an electrostatic accelerator FEL's has been demonstrated in the UCSB experiment; energy retrieval can be even better in a straight geometry tandem FEL configuration [8]. Following the design scheme of the FOM–FEM (designed to operate with 2 MeV, 12 A beam and producing 1 MW CW of radiation power) [13], we illustrate in Fig. 4 a conceptual design of a compact, moderate energy tandem EA–FEM for power beaming application. The straight geometry of the tandem FEL configuration avoids e-beam current loss in dispersive magnetic bends and in other electron optical elements. A tandem EA–FEL using a multistage depressed collector (based on design techniques used in state-of-the-art high-power microwave tubes) can attain a very high-total energy efficiency even for large energy spreads in the e-beam after the FEL interaction (corresponding to high-extraction efficiency).

In the following we present some of the design consideration of an EA–FEM intended for power beaming.

A. Average Power

The maximal average power attained from the FEM is given by

$$P_{\text{out}} = \eta_{\text{extr}} V_k I_0 \tag{2}$$

where V_k is the acceleration voltage, I_0 is the e-beam current and η_{extr} is the electronic radiated energy extraction efficiency (from the e-beam in the interaction region). An explicit expression for the extraction efficiency is given in Appendix A by (A.6).

It can be shown [14] that in the relativistic limit the extraction efficiency in the low gain regime can be approximated by

$$\eta_{\text{ext}} \approx 1/2N_w \tag{3}$$

where N_w is a number of periods in an untapered wiggler. Thus, shortening the wiggler results in increased extraction efficiency, while the gain is reduced. In high-power FEM's for power beaming the wiggler should be designed to contain $N_w \sim 10$ periods, providing an extraction efficiency of a few percents (∼5%). Shortening of the wiggler to improve the extraction efficiency, depends on the possibility to maintain a gain values larger than the cavity loss.

Further energy conversion efficiency enhancement can be achieved by employing a tapered wiggler [15] and depressed collector [10]–[13] schemes (operation of an FEL as an amplifier at a total efficiency exceeding 30% with a tapered wiggler was reported in [15]).

We point out that according to (A.6), the FEM extraction efficiency is determined by the initial detuning parameter of the electrons θ. In order to extract more power from the electrons and thus further improve efficiency of a low-gain FEM oscillator of gain bandwidth $-2\pi < \theta < 0$, one should operate the FEM at the lowest possible detuning parameter, $\theta \approx -2\pi$. Such detuning should enable an increase of efficiency by a factor of two relative to operation at the maximum gain detuning value $\theta \approx -2.6$. Studies recently carried out by us at Tel-Aviv University on an RF prebunched FEM operating near 5 GHz confirm this effect; increased extraction efficiency was obtained with a uniform (untapered) planar wiggler at an eigenfrequency bellow the maximum gain eigenfrequency, by use of e-beam prebunching at that frequency [16].

B. Gain

EA–FEM's designed to operate as an oscillator will typically operate in the low-gain regime because of the relatively short wiggler used (resulting in high efficiency). The reduction in gain, due to the short interaction length, can be compensated by use of a high e-beam current, which may be several amperes. Operating a 0.5–3 MeV electrostatic accelerator FEM with such high-beam currents results in FEM operation in the collective regime.

The small-signal gain can be calculated using the well-known single-mode gain expression [19] for an FEL operating in the linear collective regime (see Appendix A).

C. Amplifier Versus Oscillator

In the present work we considered only an oscillator configuration. Most EA–FEL's are designed as oscillators [10]–[13], probably because in order to obtain a high-gain amplifier, a high beam current (at moderate voltage) and a long (tapered) wiggler are required. This implies difficulties in electron beam transport, which pose a major obstacle to CW FEL design (see Section III-E). High-power high-gain mm wave FEM amplifiers have been demonstrated operating with short pulse duration [17], [18]. One has yet to show whether it will be possible to operate such devices in the CW mode.

If moderate-power high-gain FEL amplifiers become available at moderate cost, they may have an advantage in energy transmission schemes utilizing antenna arrays instead of a single large transmitting antenna. Phase locking of the amplifier outputs feeding the individual antenna elements, may be advantageous for beam stabilization and steering [3].

D. Optimal Out-Coupling and Circulated Power

Nonlinear simulations of an FEM oscillator and measurements of the TAU prebunched FEM performance [16] show that there exists an optimal value of resonator out-coupling coefficient T for which the output power is maximal. In that case, saturation occurs exactly at the end of the interaction region, and the output power is given by (2).

The circulating power in the cavity is given approximately by

$$P(L_w) = GP(0) = \frac{G}{G-1}P_{\mathrm{out}}$$
$$P(0) = \frac{1-T}{T}P_{\mathrm{out}} = \frac{P_{\mathrm{out}}}{G-1} \tag{4}$$

where G is given by (A.1). Observe that with moderate gain $G \approx 2$ and for high continuous output power $P_{\mathrm{out}} \approx 200$ kW, the circulating power is between $P(0) \approx 200$ kW to $P(L_w) \approx 400$ kW. One should consider the power losses in the RF cavity and verify that the expected heat load is acceptable and that RF breakdown is avoided.

E. e-Beam Transport

Careful attention should be paid to the design of the electron beam transport in a high average power FEM. For efficient FEM operation it is very important for the e-beam to be transported through the entire accelerator with minimal current interception by the acceleration and deceleration tubes and by the high voltage terminal. In electrostatic accelerators, only the intercepted current must be supplied at high voltages. The transported current is larger by a factor $1/(1-\eta_t)$ than the charging current where η_t is the transport efficiency. For $\eta_t = 99.9\%$ the transported beam current is 1000 times larger than the charging current; it can be collected efficiently at very low voltage with respect to the cathode.

We note that commercial Van de Graaff charging systems or high voltage power supplies can provide several milliamperes of charging current. In order to enable accelerator beam currents of several amperes to pass through the HV terminal, the transport efficiency should be better than 99.9% (99.7% was already demonstrated by the UCSB group with a tandem accelerator of folded electron-optical geometry at an energy of 6 MeV).

F. Heat Dissipation

Tremendous energy waste and heat dissipation are normally associated with generation of high electromagnetic radiation power if no e-beam energy recovery is used. This limits the amount of electromagnetic power that may be available from the device. In EA–FEM heat dissipation can be reduced drastically by use of a multistage depressed collector. Let us assume that the electron beam energy spread due to the FEL interaction is of the order of the average energy extraction from the e-beam due to conversion to radiated energy. In this case, a single stage depressed collector voltage relative to the cathode should equal twice the average energy loss of the electron beam in the radiation process. This means that the fraction of the e-beam power that turns into heat at the collector is near to twice the electronic extraction efficiency of energy from the e-beam. The energy dissipated at the collector into heat is, thus, about equal to the radiated power.

One should note that the power supplied to the transported electron beam, which turns partly into radiation in the interaction region and partly into heat at the collector, comes entirely from the depressed collector power supplies. The only power needed from the accelerator HV power supply corresponds to the power required to sustain the inevitable leakage current (in order to keep the terminal voltage constant).

Since radiated power levels are of the order of hundreds of kW (up to several MW), use of a single stage depressed collector will not provide the required efficiency and will lead to problems of great collector heat dissipation. It is, thus, advisable to use a multistage depressed collector, in which each energy group of the spent electrons is collected by a different collector segment of corresponding voltage.

The efficiency of a multistage collector FEM is significantly higher than that of a single stage collector FEM, and thus the heat load on the collector may be greatly reduced. The multistage collector system and its power supply using stepped voltages in the range of a few hundred kV and a total current of 10 A is within the current state of the art as demonstrated by the design of the FOM 1 MW CW FEM [13].

IV. Conceptual Design of EA–FEM for Power Beaming

A conceptual design of a compact (0.5–3 MeV), electronically charged EA–FEM is shown in Fig. 4. It is based on commercially available dc voltage power supplies or electrodynamically charged accelerators. The FEM dimensions may be substantially reduced in comparison to the Van de Graaff electrostatic accelerators used in some FEL experiments [10]–[12].

This design contains accelerating and decelerating tubes, a high-voltage terminal, where a magnetostatic wiggler with a mm-wave resonator is placed, an electromagnetic radiation out-coupling system, and a depressed collector. Use of a depressed collector as part of a high quality electron-optical system designed to reach high (up to 99.9%) e-beam transport efficiency should enable achievement of long pulse FEM operation (up to CW operation). The depressed collector reduces the kinetic energy of the electrons enabling their collection at low voltage and therefore with a high efficiency. Thus, high power conversion efficiency is obtained. The basic parameters of an EA–FEM required for the power beaming application and its performance are presented in Table II, indicating a potential for producing radiation in the range of 10 kW to 3 MW power levels.

In Table III we present specific design parameters of compact EA–FEM's intended to operate at moderate powers (100–200 kW) with voltages of 0.52 and 1.11 MV at frequencies of 35 GHz and 94 GHz, respectively. In order to attain high extraction efficiencies without tapering and with reason-

TABLE II
ELECTROSTATIC ACCELERATOR FEM PARAMETERS FOR POWER BEAMING AT MILLIMETER WAVELENGTHS

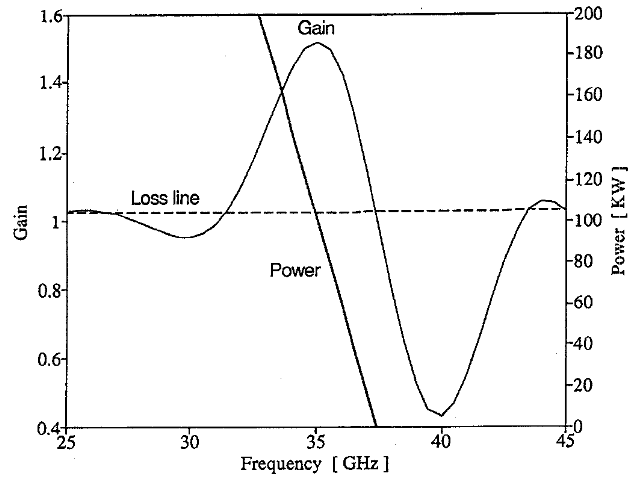
Accelerating voltage - V_k	.5-3 MeV	
Electron beam current - I_0	1-10 A	
Transport efficiency	99.9%	
Intercepted current	1-10 mA	
Beam energy	.5-30 MW	
Extraction efficiency	No prebunching	2-5%
(No wiggler tapering)	With prebunching	4-10%
Radiation power	10 kW-3 MW	

TABLE III
OPERATING PARAMETERS OF A COMPACT EA–FEM

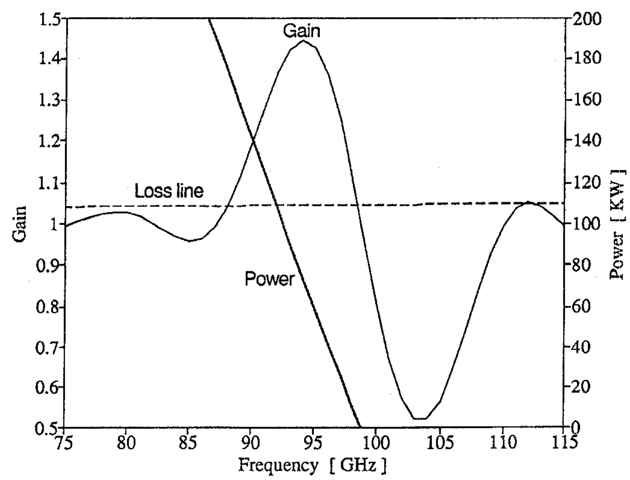
Operating frequency	35 GHz	94 GHz
Accelerator:		
e-beam current	5 A	
Accelerating voltage	520 kV	1.11 MV
Wiggler:		
Wiggler type	Magnetostatic planar wiggler	
Magnetic induction	1 kGs	2 kGs
Wiggler period	4 cm	
Number of periods	10	
RF cavity:		
Waveguide type	Rectangular	
Cross-section dimensions	15×15 mm^2	
Operating mode	TE_{01}	

able gain we have chosen a short ($N_w = 10$) magnetostatic wiggler. The RF cavity is a rectangular waveguide, having a cross section of 15×15 mm^2 operating in the TE$_{01}$ mode in an oscillator configuration. The operating voltages were chosen as so to provide maximal gain at frequencies of $f = 35$ GHz and $f = 94$ GHz, respectively. Small-signal gain calculations were made using the well-known single-mode gain expression (A.1) for an FEM operating in the linear regime. The gain-frequency dependencies calculated for operating frequencies of $f = 35$ GHz and of $f = 94$ GHz are shown by the solid curves in Fig. 5(a) and (b), respectively. The dotted curves in these figures represent the ohmic losses of the waveguide calculated for a copper waveguide. The extracted power was estimated by using (2) and (A.6), and is shown in Fig. 5 by the heavy solid line.

These design examples illustrate the possibility to attain appreciable power levels in the range required for the discussed application, even with simple designs. With some refinements, it may be possible to increase the radiated power of these devices using the above mentioned moderate voltage power supplies. This may be achieved either by use of a higher current beam (e.g., 17 A transport at 450 kV was demonstrated in the University of Maryland [18] using a sheet electron beam), or by use of extraction efficiency enhancement schemes.



(a)



(b)

Fig. 5. Performance parameters of an EA–FEM: gain (solid curves), extracted power (heavy solid curves) and resonator ohmic losses (dotted curves). (a) Operating frequency near 35 GHz. (b) Operating frequency near 94 GHz.

V. EXTRACTION EFFICIENCY IMPROVEMENT

As we see from Fig. 5 the maximal extracted power is achieved at a frequency different from the maximal gain frequency. As can be seen from the curves, the RF power and the energy extraction efficiencies can be increased by almost a factor of two, if the FEM oscillator is forced to operate away from the maximum gain detuning point using e-beam prebunching [16] or seed radiation injection. Further efficiency enhancement can be attained using wiggler tapering schemes [15].

VI. CONCLUSIONS

A compact EA–FEM design concept for power beaming at millimeter wavelengths was presented. This design is based on the use of dc high-voltage power supplies, a short magnetostatic planar wiggler, a rectangular waveguide resonator, an RF prebuncher allowing oscillation mode selection, and a multistage depressed collector. The last two features allow achievement of long pulse FEM operation (up to CW operation), and of high-power conversion efficiency.

The FEM parameters and special design and operation features required in FEM for power beaming, such as operating frequency, output power, spectral purity, energy conversion efficiency via use of depressed collector, and continuous operation possibility, were studied. On the basis of these studies the necessary parameters and features of an EA–FEM were determined, taking into account atmospheric transmission characteristics and sizes of the rectenna and of the transmitting antenna.

Appendix A
Small Signal Gain of FEL and its Energy Extraction Efficiency

When an FEL is operating in the low gain collective regime, the small signal gain is described by [19]

$$G = \frac{Q}{2\theta_{pr}}\left\{\frac{\sin^2[(\theta+\theta_{pr})/2]}{[(\theta+\theta_{pr})/2]^2} - \frac{\sin^2[(\theta-\theta_{pr})/2]}{[(\theta-\theta_{pr})/2]^2}\right\} \tag{A.1}$$

where

$$Q = \frac{e}{8mc}\,\frac{I_0}{\gamma^3\gamma_z^2\beta_z^3}a_w^2 L_w^3 \frac{(k_z+k_w)^2}{\omega} \cdot \frac{Z_{EH}}{A_{emx}}[J_0(\alpha)-J_1(\alpha)]^2 \tag{A.2}$$

is the gain parameter

$$\theta = \left[\frac{\omega}{V_z} - (k_z+k_w)\right]L_w \tag{A.3}$$

is the initial detuning parameter of the electrons injected into the interaction region and

$$\theta_{pr}^2 = \tilde{r}^2 \frac{e}{\gamma\gamma_z^2 m\varepsilon_0}\,\frac{I_0}{\pi r_e^2}\,\frac{L_w^2}{V_z^3} \tag{A.4}$$

is the reduced space-charge parameter, $\tilde{r}$ is the plasma frequency reduction factor, r_e is the e-beam radius

$$\gamma = 1 + \frac{E_k}{mc^2}, \gamma_z = \frac{\gamma}{\sqrt{1+a_w^2/2}}, a_w = \frac{eB_w}{k_w mc},$$
$$\beta_z = \sqrt{1-1/\gamma_z^2}, V_z = c\beta_z$$

B_w is the wiggler magnetic induction, E_k is the kinetic energy of electrons, $k_w = 2\pi/\lambda_w, \lambda_w$ is the wiggler period and $L_w = N_w\lambda_w$ is its length, N_w is the number of periods in an untapered planar wiggler

$$\alpha = \frac{\omega}{8\beta k_w c}\left(\frac{a_w}{\beta\gamma}\right)^2\left[1 - \frac{1}{2}\left(\frac{a_w}{\beta\gamma}\right)^2\right]^{-3/2}$$
$$\beta = \sqrt{1-1/\gamma^2}$$

J_0, J_1 are Bessel functions, k_z, Z_{EH} and A_{emx} are the longitudinal wavenumber, wave impedance and effective mode area of the operating mode, respectively. The effective mode area is defined by

$$A_{emx} = \frac{Z_{EH}\int[\boldsymbol{E}(x,y)\times\boldsymbol{H}^*(x,y)]_z\,dx\,dy}{|E_x(0,0)|^2} \tag{A.5}$$

where the integration is carried out over the waveguide cross section, $\boldsymbol{E}$ and $\boldsymbol{H}$ are electric and magnetic fields of the operating mode, and $E_x(0,0)$ is calculated on the waveguide axis, x is the wiggling direction, y is the direction of the wiggler's magnetic field, z is the waveguide axis.

The extraction efficiency at a frequency ω can be calculated according to [16]

$$\eta_{\text{extr}} = -\frac{\gamma}{\gamma-1}\gamma_z^2\beta_z^2\frac{V_z}{\omega}\,\frac{\theta}{L_w}. \tag{A.6}$$

References

[1] W. C. Brown, "Experiment involving a microwave beam to power and position a helicopter," *IEEE Trans. Aerosp. Electron. Syst.*, vol. AES-5, pp. 692–702, Sept. 1969.

[2] ——, "The history of power transmission by radio waves," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-32, pp. 1230–1242, Sept. 1984.

[3] J. Benford and R. Dickinson, "Space propulsion and power beaming using millimeter systems," in *SPIE, Intense Microwave Pulses*, vol. 2557, 1995, pp. 179–192.

[4] M. Onda, Y. Morikawa, N. Nagayava, and I. Suzuki, "A stratospheric unmanned powered lighter-than-air platform for the Antarctic ozone hole observation and long endurance communication relay," in *ICAS and AIAA-92-1.2.3*, 1992, pp. 198–208.

[5] P. Koert and J. T. Cha, "Millimeter wave technology for space power beaming," *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 1251–1258, June 1992.

[6] T. Yoo and K. Chang, "Theoretical and experimental development of 10 and 35 GHz rectennas," *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 1259–1266, June 1992.

[7] P. W. van Amersfoort, H. Urbanus, A. G. A. Verhoeven, A. Verheul, A. B. Sterk, A. M. van Inden, and M. J. van der Wiel, "An electrostatic free electron maser for fusion: Design consideration," *Nucl. Instrum. Method Phys. Res.*, vol. A304, pp. 168–172, 1991.

[8] A. Gover, A. Friedman, and A. Drobot, "Electrostatic free-electron lasers have many uses," *Laser Focus World*, pp. 95–104, Oct. 1990.

[9] I. Kind and L. R. Elias, "Electrostatic-accelerator FEL's for power beaming," *Nucl. Instrum. Method Phys. Res.*, vol. A358, pp. 186–188, 1995.

[10] L. R. Elias, "Free-electron laser research at the University of California, Santa Barbara," *IEEE J. Quantum Electron.*, vol. QE-23, pp. 1470–1475, Sept. 1987.

[11] L. R. Elias, J. Hu, and G. Ramian, "The UCSB electrostatic accelerator free-electron laser: First operation," *Nucl. Instrum. Method Phys. Res.*, vol. A237, pp. 203–206, 1985.

[12] A. Gover, Y. Pinhasi, J. Wachtell, Y. Yakover, J. Sokolowski, M. Ben Ari, B. Mandelbaum, A. Rosenberg, Y. Shiloh, G. Hazak, O. Shahal, and A. Wolf, "The Israeli tandem electrostatic accelerator FEL-status report," *Nucl. Instrum. Method Phys. Res.*, vol. A331, p. ABS20, 1993.

[13] W. H. Urbanus, R. W. B. Best, W. A. Bongers, A. H. van Inden, P. Manintveld, A. S. Sterk, A. G. A. Verhoeven, M. J. van der Wield, M. Caplan, V. B. Bratman, G. G. Denisov, A. A. Varfolomeev, and A. S. Khlebnikov, "Design of the 1 MW, 200 GHz, FOM fusion FEM," *Nucl. Instrum. Method. Phys. Res.*, vol. A331, pp. 235–240, 1993.

[14] A. Gover, H. Freund, V. L. Granatstein, J. H. McAdoo, and Cha-Mei Tang, "Basic design consideration for free-electron lasers driven by electron beams from rf accelerator," in *Infrared and Millimeter Waves*, K. J. Button, Ed. New York: Academic, 1984, vol. 11, part III.

[15] T. J. Orzechowski, B. R. Andersen, J. C. Clark, W. M. Fawley, A. C. Paul, D. Prosnitz, E. T. Scharlemann, S. M. Yarema, D. B. Hopkins, A. M. Sessler, and J. S. Wurtele, "High-efficiency extraction of microwave radiation from a tapered-wiggler free-electron laser," *Phys. Rev. Lett.*, vol. 57, pp. 2172–2175, Oct. 1986.

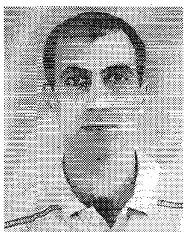
[16] A. Abramovich, Y. Pinhasi, V. Shterngartz, L. Gilutin, H. Kleinman, A. Eichenbaum, I. M. Yakover, M. Cohen, A. Gover, B. Levush, T. M. Antonsen, and V. L. Granatstein, "Measurements and simulation

of the radiation build-up process in a prebunched free-electron maser oscillator," accepted for publication in *Nucl. Instrum. Method. Phys. Res. A*, 1996.

[17] D. E. Pershing, R. D. Seelly, R. H. Jackson, H. P. Freund, "Amplifier performance of the NRL ubitron," *Nucl. Instrum. Method. Phys. Res.*, vol. A358, pp. 104–107, 1995.

[18] S. W. Bidwell, D. J. Radack, T. M. Antonsen, Jr., J. H. Booske, Y. Carmel, W. W. Destler, V. L. Granatstein, B. Levush, P. E. Latham, I. D. Mayergoyz, and Z. X. Zhang, "A high-average power tapered FEL amplifier at submillimeter frequencies using sheet electron beams and short-period wigglers," *Nucl. Instrum. Method. Phys. Res.*, vol. A304, pp. 187–191, 1991.

[19] A. Gover and P. Sprangle, "A unified theory of magnetic bremsstrahlung, electrostatic bremsstrahlung, Compton-Raman scattering, and Cerenkov-Smith-Purcell free-electron lasers," *IEEE J. Quantum Electron.*, vol. QE-17, pp. 1196–1215, July 1981.



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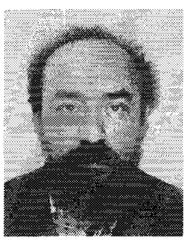

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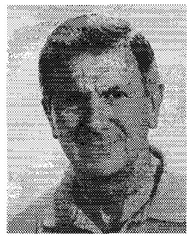

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