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FREE ELECTRON LASER FOR TRANSMISSION OF ENERGY IN SPACE

By

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16. Abstract

Potential applications and requirements for a space-based laser are discussed. The advantages of a free electron laser for use in space and its essential features are described. A one-dimensional resonant-particle model of the FEL is used to calculate laser gain and conversion efficiency of electron energy to photon energy. The optical beam profile for a resonant optical cavity is included in the model as an axial variation of laser intensity. The electron beam profile is matched to the optical beam profile and modeled as an axial variation of current density. Effective energy spread due to beam emittance is included. Accelerators appropriate for a space-based FEL oscillator are reviewed. Constraints on the concentric optical resonator and on systems required for space operation are described.

An example is given of a space-based FEL that would produce 1.7 MW of average output power at 0.5 μm wavelength with over 50% conversion efficiency of electrical energy to laser energy. It would utilize a 10 m-long amplifier centered in a 200 m-long optical cavity. A 3-amp, 65 meV electrostatic accelerator would provide the electron beam and recover the beam after it passes through the amplifier. Three to five shuttle flights would be needed to place the laser in orbit.

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SUMMARY

In this study, we have developed a conceptual design for a free electron laser (FEL) that could be used to transmit energy in space. A one-dimensional resonant particle model of the interaction of an electron beam with the laser electric field and the magnetic field of a periodic magnetic array is used to calculate laser gain and the fraction of the electron energy converted to photon energy in the FEL amplifier. It is assumed that a concentric resonator cavity is employed to produce a long, narrow, high-intensity beam inside the amplifier as well as a sufficiently large beam diameter at the cavity end mirrors to prevent mirror damage.

For efficient conversion of electron energy to photon energy, an electron beam with very low energy spread and beam emittance is required. Electrostatic accelerators were found to have beam properties that are well-matched to the requirements of the FEL. When the electron current and energy are recovered after passage through the FEL amplifier, high-current continuous operation can be achieved.

To produce light at visible wavelengths an electron beam energy in the range of 50-100 MeV would be required. Electrostatic accelerators have not yet been built to operate at these high energies. Development of a low-mass high-voltage electrostatic accelerator or an alternative accelerator system with beam quality and energy recovery efficiency comparable to the electrostatic accelerator would be a key element of any program to operate an FEL in space.

From our modeling calculations, we found that an FEL with an output power above a megawatt could be built with reasonable system parameters. As an example, we considered an FEL oscillator system in which a 3-amp, 65-MeV electron beam is used to produce 0.5 μm laser light while passing through a 10-m-long amplifier. It was calculated that almost 2 MW of optical power would be produced which, after accounting for losses in the optical system, would result in 1.7 MW of laser output power. For this output power it is estimated that the power specific mass of the laser system would be in the range of 40-80 kg/kw. The overall conversion of electrical power to laser light in this example, was 54%. The length of the optical cavity needed to prevent mirror damage was 200 M. It is estimated that the entire laser system could be put into orbit with 3 to 5 shuttle flights.

A more detailed analysis of the FEL is needed using a two or three dimensional computer simulation code to investigate the quality and focusability of the emitted laser light and to evaluate the effects of radial variations of electron density, laser intensity, and magnetic field on laser gain.

I. INTRODUCTION

Potential uses of high power lasers in space have been under study for several years.[1] Some of the uses that have been identified are:

1. Transmitting power from a central space laser station to other space stations and receivers for propulsion, electric power, material processing, or other energy requirements.
2. Beaming power from space to earth to provide energy for electric power, materials processing, or fuel production.
3. Beaming power from space to earth for laser-powered aircraft.

The advantage of using a large orbiting laser to provide power to other space vehicles is that the mass of the system required to collect the laser light and convert it to useful power could be significantly less than the mass of an onboard power supply or the mass of solar collectors needed to provide an equivalent amount of power. This advantage is particularly important where the laser power provides the energy for vehicle propulsion.

A laser that is used to transmit energy over large distances in space must fulfill a number of requirements. Some of these are:

1. The optical beam must be near-diffraction limited in order to hit a collector on the order of ten to a few tens of meters in diameter over distances of many thousands of kilometers.
2. The output power must be adequate to meet mission requirements. Output powers from about 1 MW to hundreds of megawatts would be needed for various applications.
3. The laser must be able to operate continuously over long periods of time with little maintenance.
4. The wavelength of the laser radiation must be in a region that is convenient for transmission of the laser light over large distances and for efficient conversion to useful power at the receiver. This optimum wavelength may be different for different applications and collector technologies.
5. The efficiency of the laser must be as high as possible in order to minimize system mass. This is especially true for multimegawatt systems powered by solar energy, where the mass of the solar collector and waste heat radiators may constitute most of the mass of the laser space station.

In this report, we investigate the feasibility of using a free electron laser for transmitting energy in space. The free electron laser is a new type of laser with the potential for operating at very high power and high efficiency. A detailed one-dimensional theory of FEL operation has been developed and demonstrated at a number of laser wavelengths. Two and three dimensional modeling of the FEL interaction is currently being undertaken and experiments directed at optimizing FEL performance are currently under way. An extensive collection of research work in this field can be found in references two through five.

In this study, we use a one-dimensional resonant-particle model of the FEL interaction to develop a conceptual design for a laser system that could operate at megawatt power levels and demonstrate the feasibility of using lasers to transmit energy in space.

II. ADVANTAGES OF THE FREE ELECTRON LASER FOR SPACE APPLICATIONS

The free electron laser (FEL) has a number of characteristics that make it a strong potential candidate for space applications. These are:

1. Vacuum operation
2. Potentially high output power
3. Potential high efficiency
4. Choice of operating wavelength.

Because the FEL operates in vacuum, most of the problems inherent in moving and recycling gases in gas and chemical lasers would not exist. There would be no windows or other transparent optical elements; the only optical elements would be mirrors.

Although only a small fraction of the energy of a high energy electron beam is converted to laser energy while passing through the FEL amplifier, impressive laser output powers could be achieved because the technology exists to produce very high power electron beams. For example, the power in a 100-MeV, 10-amp electron beam is 10^3 MW. Conversion of only 1 percent of this electron beam to laser light would produce 10 MW of laser power.

Efficient recovery of the electron energy not converted to photon energy is required for high laser system efficiency. If only 1 percent of the electron energy is converted to photon energy, but the energy not converted is recovered and reused with 99 percent efficiency, laser efficiency would be about 50 percent. To operate a high-power high-efficiency FEL in space it will be necessary to develop a high-voltage high-current accelerator with an efficient energy recovery system.

For a solar powered FEL, overall system efficiency would be the product of the conversion efficiency of electrical energy to laser energy and the conversion efficiency of solar energy to electrical energy. Any improvement in the technology for conversion of solar energy to electrical energy would, therefore, improve the overall efficiency of the FEL for space operation.

The optimum frequency for operation of a space-based laser may depend on mission requirements. Practically all high power lasers operate at a single frequency, which may or may not be optimum for a particular application. The FEL, however, could be designed to operate at any frequency from the infrared to the ultraviolet portion of the spectrum.

III. ESSENTIAL FEATURES OF A SPACE-BASED FEL

The primary components of a space-based FEL are shown schematically in Figure 1. A fraction of the energy of a relativistic electron beam produced in an electron accelerator is converted to photon energy in the FEL amplifier. Most of the energy not converted to photon energy is recovered and reused. Solar collectors provide makeup power, and radiator panels, some of which may be on the rear side of the solar panels, help dissipate waste heat. The FEL is assumed to be operating as an oscillator, i.e., laser energy generated in the FEL amplifier is contained in a resonant optical cavity. The high power optical beam stimulates the emission of additional light at the same frequency. A fraction of the laser light is removed on each round trip of the optical beam in the cavity. The output beam is expanded and directed toward a distant target by an optical aiming and pointing system.

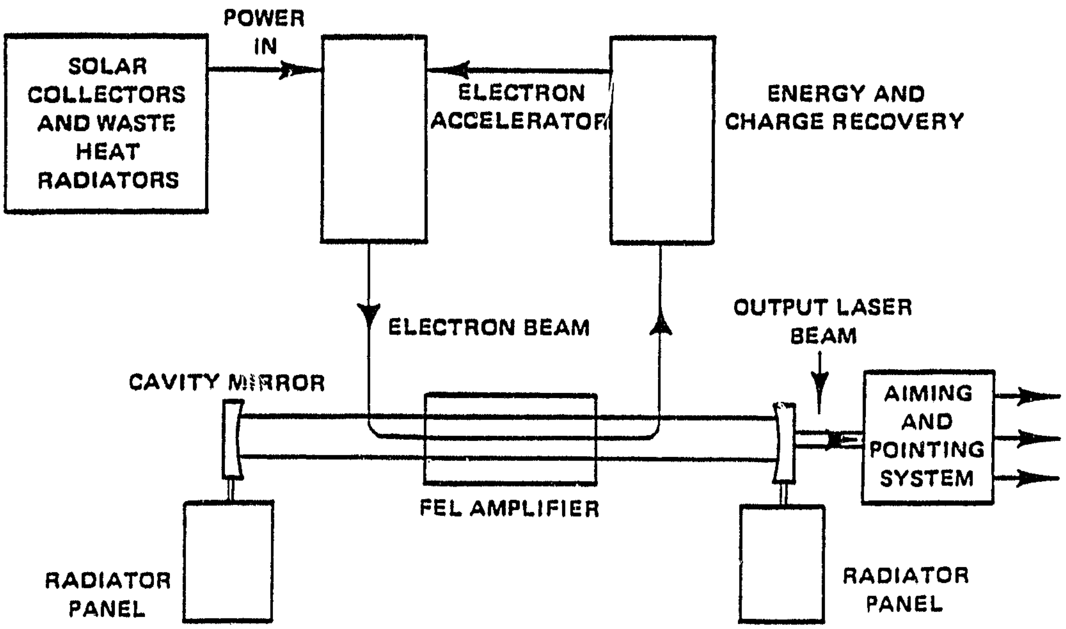

Fig. 1. Schematic diagram showing essential features of space-based FEL.

In this paper we will primarily discuss the operation of the FEL amplifier and the constraints it imposes on the optical and accelerator systems. Accelerator systems suitable for operation of an FEL oscillator will be considered and the contributions of the various components to total system mass will be estimated. A detailed discussion of solar collectors, waste heat radiators, mechanical structures, and optical aiming and pointing systems are beyond the scope of this paper. Free electron lasers in which the laser pulse is generated by another type of laser and the FEL is used only as an amplification stage will also not be discussed.

IV. EQUATIONS GOVERNING THE OPERATION OF AN FEL AMPLIFIER

A relativistic electron beam passing through a periodic magnetic array with a transverse magnetic field of magnitude B_m and spatial periodicity λ_m will produce synchrotron radiation peaked in the forward direction. The wavelength, λ_L, of the light that is produced on axis will be given in mks units by the formula[6]

$$\lambda_L = \frac{\lambda_m}{\beta_z(1 + \beta_z)\gamma^2}\left[1 + \left(\frac{e\lambda_m B_m}{2\pi mc}\right)^2\right]$$

$$\approx \frac{\lambda_m}{2\gamma^2}(1 + \alpha^2) \qquad (1)$$

where γ is the ratio of the electron energy to its rest mass energy, β_z is the axial component of the electron velocity divided by the speed of light, c, and e and m are the charge and rest mass of the electron, respectively. The quantity α is defined by equation (1). In most cases of interest α will be less than 1. The laser light, initially produced as spontaneous synchrotron radiation, will travel along with the electron beam and stimulate the emission of additional radiation. If the laser pulse is confined in an optical cavity, it will make multiple passes through the amplifier, building up in intensity until it reaches an equilibrium level at which optical gains are balanced by optical losses.

The rate at which an electron loses energy in a magnetic wiggler, neglecting spontaneous emission, is given by[7]

$$\frac{d\gamma}{dt} = -\frac{e^2}{\gamma m^2 c^2 k_m} E_L B_m \sin \psi \tag{2}$$

where E_L is the magnitude of the laser field and $k_m = 2\pi/\lambda_m$.

The combined forces of the magnetic field and the laser field on the electrons produce ponderomotive potential wells which move along with the electron beam. These potential wells define regions of longitudinal phase space in which the electrons may travel in bound or unbound orbits. The phase, ψ, of an electron is determined by its position relative to the potential well.

Bound electrons perform oscillations in the ponderomotive potential wells. These oscillations are called synchrotron oscillations. For particles near the center of the well where the axial restoring force on the electron is approximately linear, a simple expression for the angular frequency of the synchrotron oscillations can be derived. Using the expression for $d\beta_z/dt$ in reference 7 and rewriting it in the form of a pendulum equation, $\ddot{z} \approx -\Omega_s^2 z$, the synchrotron oscillation frequency is found to be

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$$\Omega_s = \sqrt{\frac{2}{c}}\,\frac{e}{m}\,\frac{(E_L B_m)^{1/2}}{\gamma}\,. \tag{3}$$

Kinetic energy of the trapped electrons may be converted to photon energy by controlling the position of the electrons relative to the ponderomotive potential wells. This may be accomplished by decelerating the potential wells (tapering the wiggler magnet)[8] or by accelerating the electrons while maintaining the velocity of the ponderomotive wave constant.[9] If the bound electrons execute a large number of synchrotron oscillations during the time they pass through the FEL amplifier, the energy transferred to the laser beam will come primarily from these bound electrons and, on average, all bound electrons will lose energy at the same rate as the resonant electron. Energy transfer from the unbound electrons to the laser beam will average to zero. If we assume the electron and laser beams are coincident, the laser gain will be given by[9]

$$\frac{dE_L}{dz} = \frac{e}{4\pi\varepsilon_0 mc^2}\,\frac{(1+\beta_z)}{\beta_z(1+\alpha^2)}\,FJ\gamma_R\lambda_L B_m \sin\psi_R \tag{4}$$

where γ_R and ψ_R are, respectively, the dimensionless energy and phase of the resonant electron and J is the electron current density. The fraction, F, of the electrons in bound orbits is given by

$$F = \frac{4e}{\pi^2 mc^2}\,\frac{\beta_z(c(1+\beta_z))^{1/2}}{(1+\alpha^2)}\,\frac{(E_L B_m)^{1/2}}{\Delta\gamma/\gamma_R}\,\lambda_L\gamma_R\eta(\psi_R)\,. \tag{5}$$

In equation (5) $\eta(\psi_R)$ is the ratio of the area of a closed orbit region of phase space of resonant phase ψ_R (decelerating bucket) to the area of a closed orbit region of zero resonant phase (stationary bucket). $\Delta\gamma/\gamma_R$ is the fractional energy spread of the electron distribution, assumed symmetric about γ_R. Equation (5) holds if the initial phase space density of the electrons is uniform in the region of phase space occupied by the electron beam and if the density of electrons in the bucket equals the initial phase space density. The value of F must always be ≤ 1.

V. CONSTRAINTS ON THE DESIGN OF AN FEL OSCILLATOR

Since the rate at which electrons lose energy is directly proportional to the magnitude of the laser field (equation (2)), it is desirable for the optical beam to be narrow inside the FEL amplifier. At the mirrors, however, the diameter of the optical beam must be large enough to prevent damage to the mirror surfaces. A concentric optical cavity in which the radius of curvature of the cavity mirrors is slightly larger than half the cavity length results in an optical beam which meets both of these requirements.

For a two-mirror symmetric resonant cavity with only the TEM_{oo} mode present, the beam profile is given by[10]

$$r(z) = r_0\left(1 + \left(\frac{z}{z_0}\right)^2\right)^{1/2} \qquad (6)$$

where

$$z_0 = \frac{\pi r_0^2}{\lambda_L} \; . \qquad (7)$$

Here r(z) is the radius at which the electric field amplitude of a beam with a transverse Gaussian profile has decreased to

1/e of its peak value. r_0 is the minimum value of r(z) at the center of the cavity. If the optical cavity is a concentric resonator,

$$r_0 \approx \frac{\lambda_L D}{2\pi r_1} , \tag{8}$$

where D is the distance between the mirrors and r_1 is the beam radius at the mirrors. For example, if the wavelength of the laser is 0.5 μm, the length of the optical cavity is 200 m and a beam diameter of 10 cm is desired at the mirrors, the beam diameter at the center of the cavity would be .064 cm. If a laser amplifier 10 m long were located at the center of the optical cavity, the optical beam diameter at the ends of the amplifier would be 0.5 cm.

To permit the optical beam to pass through the FEL amplifier without being clipped at the ends of the amplifier, the clear-through diameter should be at least 3 times the optical beam diameter, which for the above example would be 1.5 cm. The clear-through aperture for a magnetic wiggler would be about the same as the wiggler period. If we assume a wiggler period of 1.5 cm and a transverse magnetic field on axis of 2 kG, then from equation (1) the electron energy required to produce 0.5 μm laser light would be 64.5 MeV.

VI. MATCHING THE ELECTRON BEAM TO THE OPTICAL BEAM

In a field-free drift space the beam profile of a focused electron beam, neglecting space charge effects, is given by[11]

$$r(z) = r_0\left(1 + \left(\frac{z\varepsilon}{r_0^{\,2}}\right)^2\right)^{1/2}, \tag{9}$$

where ε is the electron beam emittance. For a Gaussian beam, $r(z)$ would be the radius at which the electron density has decreased to 1/e of its maximum value. From (6) and (9) the electron beam profile will be matched to the optical beam profile when

$$\varepsilon = \frac{\lambda_L}{\pi}\ . \tag{10}$$

If we compare a monoenergetic electron beam with emittance ε to a zero-emittance beam with an energy spread $\Delta\gamma$, the equivalent energy spread in the FEL amplifier will be given by[11]

$$\left(\frac{\Delta\gamma}{\gamma}\right)_{\varepsilon} = \frac{1}{2}\left(\frac{\beta\gamma\varepsilon}{\mu\rho}\right)^2, \tag{11}$$

where $\mu^2 = 1 + \alpha^2$ and ρ is the beam radius. In a field-free drift space, $\rho = r_0$ and the equivalent energy spread over the entire region is given by the value at the beam waist. The FEL amplifier is not a field free region, however, and by properly designing the magnetic fields the equivalent energy spread could, in principle, be made a function of position, so that $\rho = r(z)$ in equation (11). This might be done, for example, by contouring the wiggler field so that B_m is perpendicular to the direction of propagation of the optical beam at every point inside the wiggler and by matching the electron beam profile to the optical beam profile.

Electron beam emittance is a function of the accelerator design and, in particular, the design of the electron gun.

Using the example given in Section V, the beam emittance needed to match the electron beam profile to the optical beam profile would be 1.59×10^{-7} m-rad. Electron guns with emittance values in this range have already been demonstrated.[12]

VII. COMPUTER MODELING OF FEL PERFORMANCE

A computer code has been written based on the one-dimensional resonant particle model of the FEL described in Section IV. Using this code, we calculate laser gain and the fraction of the electron energy converted to photon energy in the FEL amplifier. The focusing and defocusing of the optical beam inside the FEL amplifier is included in the 1-D code using the optical beam profile given in Section V by assuming the laser intensity is uniform across the beam and varies only as a function of axial position. The electron beam is assumed to be of uniform density at any axial position and to match the optical beam profile in the FEL amplifier. It is also assumed that the amplifier magnetic field has been designed so that the equivalent energy spread due to emittance (equation (11)) is a function of position along the amplifier.

The computer code assumes that the closed orbit region is filled with electrons at the input end of the amplifier. If the full bucket height is greater than the electron energy spread, a short prebunching section preceding the amplifier would be needed to fulfill this condition. It is also assumed that only the trapped electrons contribute to laser gain and the contribution of the unbound electrons averages out to zero. As previously stated, this is a good approximation when the trapped electrons execute several synchrotron oscillations over the length of the wiggler. However, even if the number of synchrotron oscillations that take place is a few or less, the resonant particle model may still be used to obtain approximate scaling relations. In this case the values of laser gain and fractional energy conversion serve as upper limits to the values that would be obtained using a more detailed multiparticle simulation code to optimize the amplifier design.

In our model the value of the resonant phase, ψ_R, at the input end of the amplifier is chosen to maximize the rate of amplification at the input. As electrons progress through the amplifier, the resonant phase is varied as a function of position to maintain the ratio of the area of the closed orbit region to the effective energy spread constant. The effective energy spread is assumed to be equal to the actual energy spread produced in the accelerator, $\left(\frac{\Delta\gamma}{\gamma}\right)_{accel}$, plus the contribution to the effective energy spread due to beam emittance, $\left(\frac{\Delta\gamma}{\gamma}\right)_{\varepsilon}$. Radial variation of the amplifier magnetic field and its contribution to the effective energy spread have been neglected.

Figure 2 shows laser gain and the fraction of the electron beam energy converted to photon energy as a function of

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the input laser power to the amplifier for the parameters of the example of Sections V and VI. It is assumed that $\left(\frac{\Delta\gamma}{\gamma}\right)_{accel} = 10^{-4}$. Laser gain is found to decrease as input laser power increases since the rate at which the laser field amplitude increases is only weakly dependent on the magnitude of the laser field (equations (4) and (5)). The fraction of the electron beam energy converted to photon energy is directly dependent on E_L (equation (2)) and increases as laser power increases. For efficient operation of the laser, at least 1 percent of the electron beam energy must be converted to photon energy under equilibrium operating conditions. For the example given in Figure 2 the laser light would be amplified

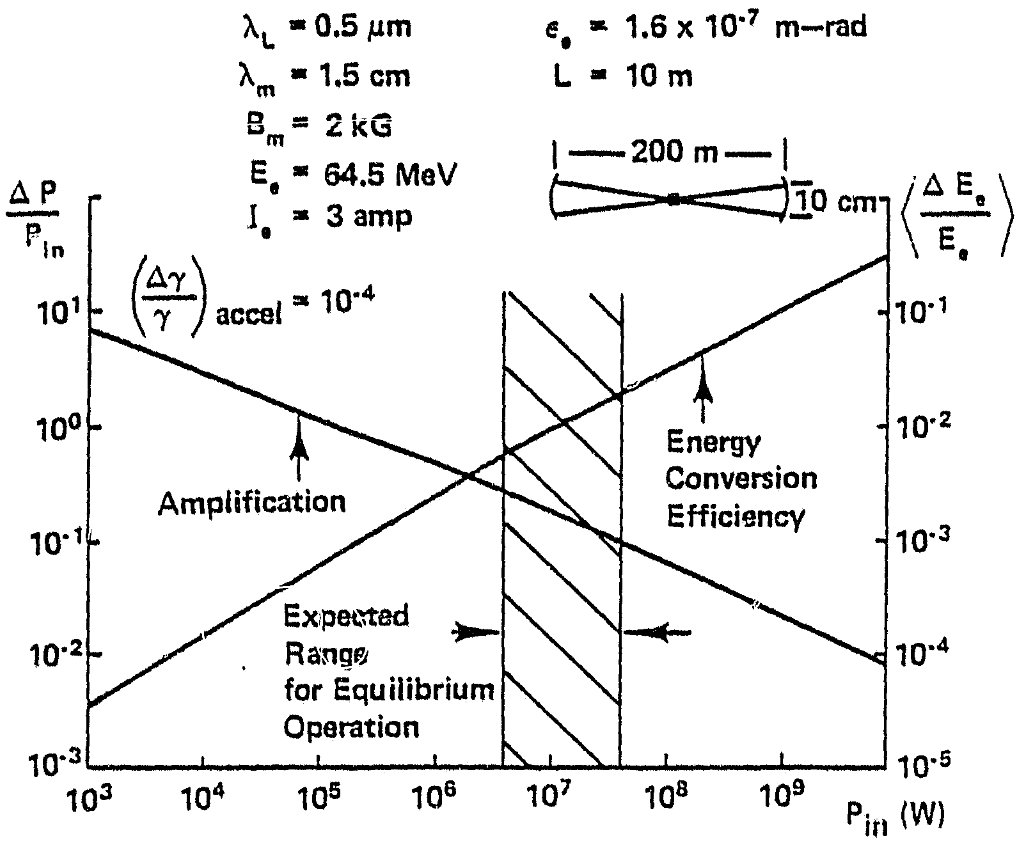

Fig. 2. Amplification and energy conversion efficiency as a function of laser power at the input end of the FEL amplifier.

by about 16 percent per pass at 1 percent fractional energy conversion and the laser power generated, if the laser were operating continuously, would be almost 2 MW (Figure 3).

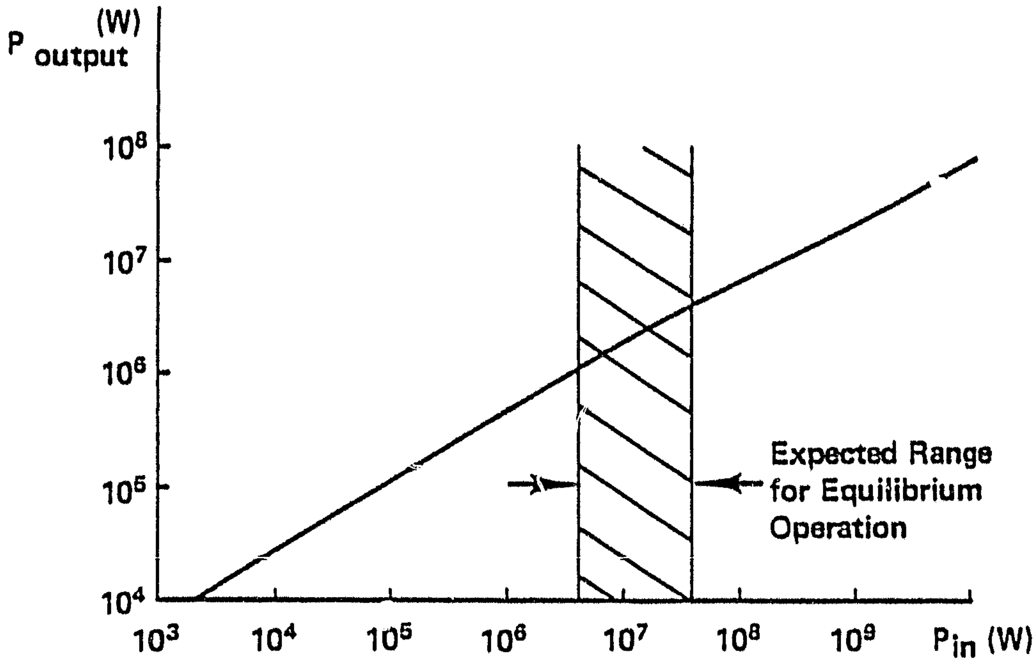

Fig. 3. Emitted laser power as a function of laser power at the input end of the amplifier for the parameters of Figure 2. Emitted power is directly proportional to energy conversion efficiency.

From equation (3) the number of synchrotron oscillations that will take place in the wiggler will be given by

$$N = \frac{1}{2\pi}\int_0^L \frac{\Omega_s}{\beta_z c}\,dz$$

$$\approx \frac{e}{\pi m \gamma_R c^{3/2}}\sqrt{\frac{B_m}{2}}\int_0^L E_L^{1/2}\,dz, \tag{13}$$

where L is the length of the FEL amplifier. For the example we have chosen, N = 1.7 when 1 percent of the electron energy is converted to laser energy.

The parameters chosen in the example of Figures 2 and 3 illustrate the basic features of a space-based FEL. These are: 1) A long optical cavity will be required to produce a high intensity laser beam in the FEL amplifier without destroying the cavity mirrors, 2) Electron beams of at least 50 - 100 MeV will be required for the production of visible light to satisfy geometric constraints in the FEL amplifier, 3) Conversion of at least 1 percent of the electron energy to photon energy will be needed for efficient laser operation, and 4) Gains of at least 10 percent per pass will be needed to keep the fraction of the emitted light lost in the optical system low.

VIII. ACCELERATORS FOR A SPACE-BASED FEL

The system we are considering for a space-based FEL has an output that is either continuous or a continuous train of short pulses. If the output were a train of pulses, the time between pulses should be no longer than the round-trip transit time of the optical beam in the resonant cavity. For a 200 m long cavity this time is 1.3 μsec. We therefore will exclude from consideration all accelerators with pulse repetition rates very much below 1 MHz. This includes induction linacs, betatrons, and other pulsed discharge type accelerators. The accelerator systems that might be used for such a laser include electrostatic accelerators, R-F linacs, and storage rings.

Electrostatic accelerators have a number of features that make them attractive for this application. The energy spread produced in the accelerator and the emittance of the electron beams are very low. This permits a large fraction of the electron beam to be trapped and contribute to laser gain (equation (5)). The pulse length of an electrostatic accelerator can be varied from hundreds of nanoseconds to continuous operation. By returning the electron beam to the accelerator after it passes through the FEL amplifier,[12] currents of the order of several amperes could be obtained, which would be adequate for this application.

Energy recovery in an electrostatic accelerator could be highly efficient, especially for electrostatic accelerators operated in the 50 - 100 MeV range. Electrons leave the dome of the accelerator with an initial energy produced by the accelerating structure of the electron gun. The kinetic energy of the accelerated electrons is the sum of the electron gun extraction energy and that acquired in the accelerating column. Energy lost by the electrons in the FEL amplifier must be $\leq$ the gun extraction energy. The kinetic energy provided by the column is recovered with essentially 100 percent efficiency when electrons travel back up the column. The remaining electron energy is recovered by a series of collecting plates at different potentials inside the dome of the accelerator. The efficiency of energy recovery by the collecting plates depends on the collector geometry and the potential difference between the plates, but might be $\geq$ 90 percent. Only a small fraction of the electron energy ($\sim$ 1 percent) need be converted to photon energy using an electrostatic accelerator to produce high overall laser efficiency. The example given in the previous sections for a space-based FEL assumed that an electrostatic accelerator would be used, and it appears that this type of accelerator would be a good choice for a first generation space-based FEL operating in the 1 - 10 MW output range.

An electrostatic accelerator with electron beam recovery and an electron current in the range of interest is presently being built and tested.[12] For space-based operation it would be necessary to design an accelerator that would:

1. Operate at higher electron energies than conventional electrostatic accelerators
2. Minimize mass by utilizing vacuum insulation rather than high pressure gas insulation where possible
3. Provide adequate makeup current for continuous operation, possibly by replacing charging chains with beam injection from a small cyclic accelerator such as a cyclotron or microtron.

Arcing and breakdown caused by space plasma may be a severe problem in the space environment,[13] particularly if vacuum insulation is employed to reduce accelerator mass. If the accelerator is not contained in a large tank of high pressure gas, it may be necessary to contain it in a large envelope to shield it from plasma currents in space.

An R-F linear accelerator could be less massive and would not have voltage breakdown problems as severe as an electrostatic accelerator. Typical pulse lengths for an R-F linac would be on the order of a few tens of picoseconds. Such short pulses would not optimally overlap with the electron beam and end effects might seriously degrade laser gain. The electron energy spread produced by an R-F linac is of the order of 1 percent, also resulting in reduced gain compared to beams with lower energy spread produced by an electrostatic accelerator. Techniques for recovery of electron energy by decelerating the electron beam in the linac after it leaves the FEL amplifier[14] would not be as efficient as energy recovery in an electrostatic accelerator, so that conversion of several percent of the electron energy to light would probably be required to attain high overall laser efficiencies. The duty cycle for an R-F linac is generally much lower than that of an electrostatic accelerator, so higher peak currents might be required to achieve the same average laser power. Nevertheless, if very high voltage electrostatic accelerators prove to be impractical in space, FEL systems could be designed for use with R-F linear accelerators. Hybrid systems, utilizing the low mass and high energy capabilities of the RF linac together with the energy recovery capability of the electrostatic accelerator, may also be possible.

Storage rings can be operated with pulse lengths much longer than those generally obtained in RF linacs and with peak currents much higher than those of either an RF linac or an electrostatic accelerator. The energy spread and beam emittance in a storage ring are also lower than for any other type of accelerator. Energy recovery is provided by continually reusing the beam. The basic problem that must be solved with the storage ring is that the energy spread induced in the electron beam in the process of converting electron energy to laser energy must be removed within the time required for the electrons to make one round trip in the ring.

Two ways have been suggested to deal with the problem of energy spread in storage rings. Smith *et al.*[15] have suggested using a wiggler design that is less sensitive to energy spread and could permit a larger spread to develop without significant reduction of laser gain. Synchrotron radiation in the ring must be relied upon to maintain the energy spread at an equilibrium level. This is a relatively slow process and limits the fraction of the electron energy that could be converted per pass to about 10^{-4}.

Kroll, Morton, and Rosenbluth[8] have suggested that the electron energy spread could be controlled using an amplifier design that first traps all the particles in the beam adiabatically, then extracts energy from the electrons by tapering the magnet, and finally restores the energy spread to its initial value by adiabatically detrapping the electrons. A significant fraction of the electron energy could be converted to photon energy per pass in such a device, but a multifunction amplifier of this kind would be very long.[16] Incorporating such a device in a space-based laser would require an optical cavity kilometers in length. On the other hand, the output powers that could be obtained with such a device are very impressive. For example, using a storage ring with a peak current of 1,000 amp at 500 MeV with a 5 percent duty cycle, the average power that would be obtained by converting 1 percent of the electron energy to photon energy per amplifier pass would be 250 MW.

We have concluded that for the first generation of space-based free electron lasers, electrostatic accelerators appear to be the best choice based on their excellent beam quality, long pulse length, efficient energy recovery, and acceptable electron beam current. A hybrid system incorporating both an electrostatic accelerator and an R-F linac may also be possible. At a later time, when very much larger systems might be needed in space, storage ring free electron lasers should be considered.

IX. LASER SYSTEM EFFICIENCY

Several factors affect the overall efficiency of the laser system. These include the conversion efficiency of solar energy to electrical energy (assuming solar energy is used to run the laser), the efficiency of the power supply that provides makeup power to the accelerator, the efficiency with which electron beam energy not converted to laser energy is recovered, and losses in the optical system.

The instantaneous power in an electron beam, P_e, is given by

$$P_e = E_e I_e \tag{14}$$

where E_e is the mean electron energy and I_e is the beam current. P_e will be in MW when E_e is in MeV and I_e is in amperes. If a fraction δ of the electron beam energy is emitted as laser light, the emitted laser power

$$P_L = \delta P_e . \tag{15}$$

Most of the energy in the electron beam will be recollected and reused. If an electrostatic accelerator is used to produce the electron beam, a power supply in the dome of the accelerator must supply energy to the electron beam to make up for energy converted to laser light, and also to cover losses that occur in the electron gun, the electron collector system, and the beam transport system. The power that must be supplied to the power supply, P_p, is given by

$$P_p = \frac{1}{\varepsilon_p}\left[P_L + P_c + P_g + P_t\right] \tag{16}$$

where ε_p is the power supply efficiency, P_c is the power dissipated in the electron collector, P_g is the power dissipated in the electron gun, and P_t is the power dissipated in the electron beam transport system.

The optical power stored in the resonant optical cavity under equilibrium conditions is given by

$$P_{cav} = \frac{P_L}{g} \tag{17}$$

where g is the FEL amplification factor ($g = \Delta P/P_{in}$ in Figure 2). Some fraction η of the laser power in the cavity is lost on each round trip of the optical beam in the resonant optical cavity. Some of the energy lost in the optical system is converted to heat energy which may be dissipated using radiator panels. If the mirrors must be maintained within a specified temperature range to prevent mirror distortion, it may be necessary to actively cool the mirrors, so that the radiator panels are at a higher temperature than the mirrors. This requires an additional energy input. The power dissipated by the mirror system and its cooling system is given by

$$P_m = \frac{\eta}{g} P_L(1 + r), \tag{18}$$

where r is the factor by which power losses are increased due to active cooling.

The conversion efficiency from electrical energy to laser power, ε_e, is given by

$$\varepsilon_e = \frac{P_L\left(1 - \frac{\eta}{g}\right)}{P_p + \frac{\eta}{g} r P_L}$$

$$= \frac{\varepsilon_P P_L\left(1 - \frac{n}{g}\right)}{P_c + P_g + P_t + P_L\left(1 + \frac{r\eta\varepsilon_P}{g}\right)} . \tag{19}$$

When $P_L >> P_c + P_g + P_t$,

$$\varepsilon_e \approx \varepsilon_P \frac{\left(1 - \frac{n}{g}\right)}{\left(1 + \frac{r\eta\varepsilon_P}{g}\right)} . \tag{20}$$

Total system efficiency, ε_T, is the product of the efficiency for conversion of solar energy to electrical energy, ε_s, and the efficiency for the conversion of electrical energy to laser energy.

$$\varepsilon_T = \varepsilon_s \cdot \varepsilon_e$$

$$\approx \varepsilon_s \varepsilon_P \frac{\left(1 - \frac{n}{g}\right)}{\left(1 + r\frac{n}{g}\right)} . \tag{21}$$

If $\frac{n}{g} << 1$, the primary factors influencing overall laser system efficiency will be the solar-to-electrical conversion efficiency and the efficiency of the accelerator power supply, both of which are independent of the FEL interaction process.

Laser system efficiency calculated for the example of Figure 2 is given in Table I along with the values of the parameters used in the calculation.

Table I

E_e = 64.5 MeV	P_e = 194 MW
I_e = 3 amp	P_L = 1.94 MW
δ = .01	P_c = 15 kw
g = .16	P_g = 3 kw
η = .02	P_t = 19.4 kw
r = .5	ε_e = .54
ε_P = .65	ε_s = .1

ε_T = .054

Efficiency is calculated under equilibrium conditions, where it is assumed that 1 percent of the electron energy is converted to photon energy. The average energy lost by an electron in the collector system will be approximately half the potential difference between adjacent collector plates. In calculating P_c, a 10 kV potential difference was assumed between collector plates so that the average energy loss per electron in the collector would be 5 keV. We assumed that 1 keV per electron would be dissipated as heat in the electron gun to obtain the value of P_g, and that 10^{-4} of the electron beam would be lost in the beam transport system to obtain the value of P_t. One percent of the laser energy is assumed to be absorbed at each mirror, reducing the power out of the laser to 1.7 MW. The electricity to run the laser is assumed to be produced by a conventional solar cell array with a conversion efficiency of 10 percent. Total electric power needed to operate the accelerator system and the heat pumps needed to cool the mirrors is 3.2 MW.

There are three areas where improvements could significantly raise overall laser efficiency:

1. Conversion efficiency from solar to electrical energy
2. Power supply efficiency
3. Mirror reflectivity.

High temperature heat engines could convert solar energy to electrical energy with higher efficiency than a solar cell array. Power conversion systems based on nonsteady gas dynamic processes[17] appear to have the potential for conversion efficiencies of up to 50 percent, and energy exchangers with a binary cycle may reach efficiencies of the order of 70 percent.[18] The factor that could result in the greatest improvement in overall laser efficiency would, therefore, be an increase in the conversion efficiency of solar to electrical energy.

Efficiency of the accelerator power supply, already assumed to be 65 percent, might be increased to as high as 80 percent, providing a small increase in laser efficiency. Improvement in optical coatings to reduce absorption at the mirrors would reduce both absorption losses and power losses in the cooling system for the mirrors. Even if mirror reflectivities were improved by an order of magnitude from the assumed 99 percent per mirror surface to 99.9 percent per surface, the overall efficiency of the laser would only increase from 5.4 percent to 6.3 percent for the above example. Assuming maximum improvement in all three areas provides an upper limit on the potential efficiency of a space-based FEL. Assuming $\varepsilon_s = .7$, $\varepsilon_p = .8$, and $\eta = .002$, the overall efficiency would increase from 5.4 percent to 54 percent.

X. SYSTEMS DESIGN CONSIDERATIONS

Many aspects of a space-based FEL system must be considered in addition to the amplifier and accelerator design in order to determine the feasibility of this concept. These include optical and mechanical systems, cooling requirements, primary power requirements, vacuum compatibility, and system mass.

1. OPTICAL SYSTEMS. As explained in Section V, a concentric optical cavity is needed for a high power FEL oscillator. To keep the cavity length as short as possible, laser intensity at the mirrors will be high. For the example we have chosen, under equilibrium operating conditions the laser intensity at the cavity mirrors would be about 160 kw/cm^2. If 1 percent of the energy were absorbed at each mirror surface, 1.6 kw/cm^2 of heat would have to be removed. The cooled mirrors required for this purpose are opaque and energy must be coupled out either through a hole in the center of the mirror or around the mirror edges. For the high Fresnel number cavities needed for this application, slightly unstable cavity configurations may be needed to couple more than a few percent of the laser light out of the cavity.[19] Further study of the output coupling problem is needed to resolve this issue.

The concentric optical cavity is only marginally stable and very small changes in cavity length can produce large relative changes in laser beam diameter at the mirrors. This can affect output coupling and may result in mirror damage if the spot size at the mirrors becomes too small. The rate of change of spot size with cavity length can be derived from the equation for the optical beam profile in a symmetric optical cavity[10] and is given by

$$\frac{dr_1}{dD} = \frac{\lambda_L^{\,2} R^3}{8\pi^2 r_1^{\,3}\left(R - \frac{D}{2}\right)^2} , \qquad (22)$$

where R is the radius of curvature of the mirrors and D is the distance between the mirrors on axis. For a concentric cavity,

$$\Delta R \equiv R - \frac{D}{2}$$

$$\approx \frac{\lambda_L^{\,2} D^3}{8\pi^2 r_1^{\,4}} . \qquad (23)$$

Substituting (22) into (23), we obtain

$$\frac{dr_1}{dD} \approx \left(\frac{\pi}{\lambda_L}\right)^2 \frac{r_1^{\,5}}{D^3} . \qquad (24)$$

For $\lambda_L = 0.5\ \mu m$, $r_1 = 5$ cm, and D = 200 m, we obtain $\Delta R = .405$ cm and $dr_1/dD = 1.54$, so that a change of 1 cm in a cavity 200 m in length would produce a change of 1.54 cm in beam radius.

Accurate alignments and positioning of optical components is essential for laser operation. Distortion of the space frame due to thermal or mechanical stresses can disrupt this alignment. To minimize thermal distortions, it may be necessary to shield the framework supporting the optical cavity from direct sunlight. Compensation for small distortions in the space structure may be accomplished using an interferometric alignment system with mechanical feedback.[20]

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2. RADIATIVE COOLING. In space, radiative cooling must be employed to dispose of heat. The rate at which heat is radiated is governed by the Stefan-Boltzman equation

$$\frac{dE}{dt} = 5.67 \times 10^{-8} \varepsilon T^4, \tag{25}$$

where ε is the emissivity of the radiator ($\varepsilon = 1$ for a black body) and dE/dt is in watts/m^2 when T is in degrees Kelvin. The rate at which heat is dissipated can be increased by adding radiator panels to the system. The temperature of heat-generating components can be further controlled using heat pumps.

Figure 4 shows the radiator area required to dispose of 1 MW of waste heat as a function of radiator temperature. The lower curve shows the radiator area when no heat pumps are used and the heat-generating components are at the same temperature as the radiator panels. The upper curve shows the radiator area required when heat pumps are used to maintain all heat-generating components at 300°K. Because heat pumps introduce additional complexity, and the energy consumed in their operation must be supplied by increasing the size of the solar collector array, it would probably be best to use them only for critical system components such as cavity mirrors. Other heat-generating components could be maintained at about 400°K by the proper choice of radiator area.

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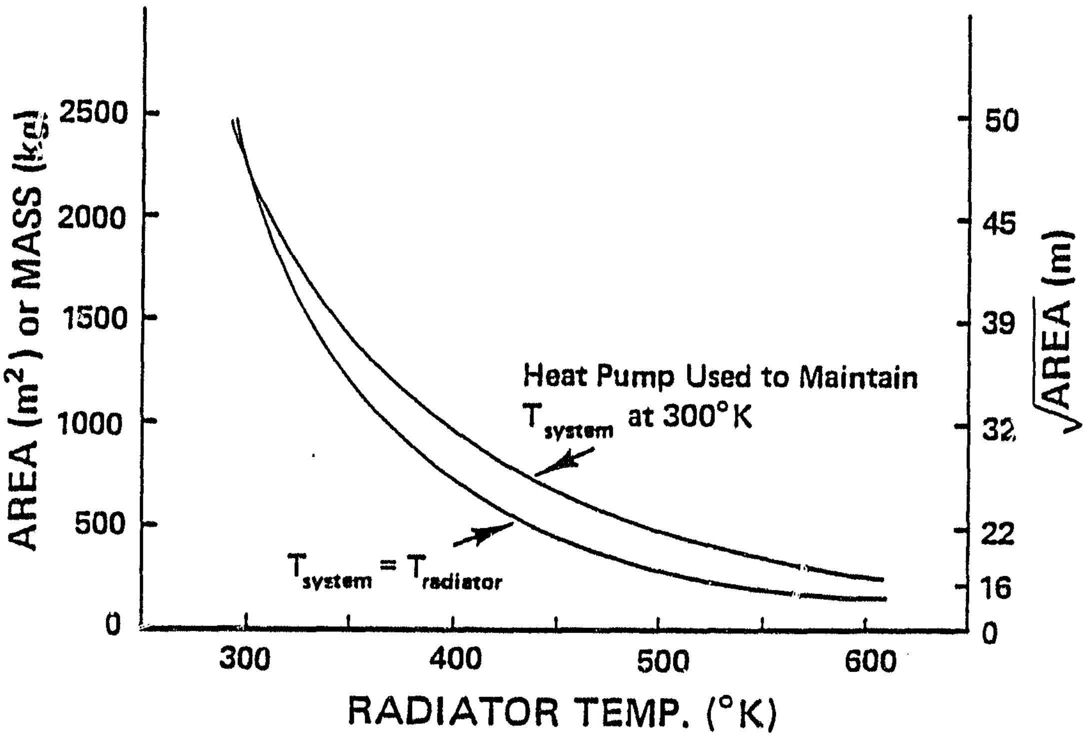

Fig. 4. Radiator area needed to dissipate 1 MW of waste heat. The emissivity is assumed equal to .95. The upper curve is obtained assuming a heat pump with ideal thermodynamic efficiency. If only the mirrors are maintained at 300°K, the radiator area required per megawatt of heat generated in the laser will lie between the two curves.

3. PRIMARY POWER SYSTEM AND VACUUM COMPATIBILITY. Electric power could be provided either by solar collectors or a nuclear generator. In our example we have assumed that solar power is used. The area of a photovoltaic array needed to provide 3.2 MW of electrical power at 10 percent conversion efficiency is 2.3×10^4 m^2.

A large high-voltage solar array must be carefully designed to prevent arcing that can reduce collector efficiency. Indeed, all electrical components must be designed to be vacuum compatible. This may require shielding from plasma currents and ionizing radiation that are present in the space environment.[13] If a photovoltaic array is used it may be necessary to apply a transparent insulating coating to the array. Some of the measures that may be required to operate high voltage systems in a space environment could significantly affect system mass.

4. SYSTEM MASS. Mass is an important factor in determining the feasibility of any space system. Table II gives estimates of mass for the components of a 1.7 MW output system.

Table II

Contributions to System Mass

	Mass/10^4 kg
Solar Collectors	2.4 - 4.8
Heat Radiators	0.1 - 0.2
Accelerator	2.0 - 4.0
FEL Amplifier and Electron Optics	0.4 - 0.6
Laser Optical Systems	1.0 - 2.0
Structural Components	0.5 - 1.0
Other (8 percent of above)	0.5 - 1.0
Total System Mass	6.9 - 13.6

The mass of photovoltaic arrays currently used in space is about 15 kg/kw. The low estimate for solar collector mass in Table II assumes that improvements in photovoltaic or alternative solar conversion systems may reduce this value by a factor of 2. Heat radiators can be made with a mass ≤ 1 kg/m^2. 1.5 MW of waste heat must be radiated for this case so that from 1,000 to 2,000 m^2 of radiator area would be needed depending on the operating temperature of the radiator. The low estimate for accelerator mass is obtained from the mass of the field plates, support structure, and charging mechanism of a conventional electrostatic accelerator assuming vacuum insulation is used to prevent electrical breakdown and that aluminum is the structural material. If the accelerator must be encased in a tank of high pressure insulating gas, this would double the weight. The estimate for the mass of the optical systems was obtained from extrapolating the mass of the Orbiting Astronomical Telescope, assuming the aiming and pointing system is composed of a seven-element mirror 10 meters in diameter. Using the total masses in Table II and an output power of 1.7 MW results in a power specific mass of 41-80 kg/kw.

The Space Shuttle can carry a payload of about 3×10^4 kg per flight, so that the laser system would represent from 2.3 to 4.5 Shuttle payloads.

XI. CONCLUSIONS

Calculations based on a modified one-dimensional resonant particle model of the FEL indicate that a high-power, high-efficiency space-based laser with reasonable system parameters could be built for transmission of energy in space. More detailed studies are needed to determine whether the optimistic results obtained using the 1-D model remain valid when multidimensional effects are included. In particular, the quality and focusability of the output beam must be determined.

Further study is also required of problems associated with the operation of a high voltage electrostatic accelerator to determine its feasibility for use in a first generation space-based FEL. In particular, the accelerator would have to be redesigned to minimize its mass, and problems associated with its interaction with the space environment would have to be addressed.

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