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Free Electron Lasers in Strategic Defense

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Gregory H. Canavan
John C. Browne

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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FREE ELECTRON LASERS IN STRATEGIC DEFENSE

by

Gregory H. Canavan and John C. Browne

ABSTRACT

This report discusses the basis for free electron laser (FEL) operation, roles FELs could play in strategic defense, expected effectiveness, and status of key components. The constellation sizes needed to meet evolving threats are derived, and the tradeoffs between space and ground basing of FELs are discussed, leading to a conclusion that FELs could be available for and play complementary roles to those of kinetic energy concepts.

I. INTRODUCTION AND SUMMARY

This report discusses the physical basis for the operation of free electron lasers (FELs), the roles they could play in strategic defense, and their expected effectiveness. Section II describes FEL principles and operation and the status of key components needed to scale FELS to high power and brightness. Section III discusses the constellation sizes needed to meet evolving threats; IV reviews the tradeoffs between space and ground basing of FELs; and V discusses their countermeasures. Section VI evaluates their overall scaling and performance relative to projected threats and alternative ways of meeting these threats. We conclude that FELs could play important roles that were complementary to those of kinetic energy concepts in all time intervals.

The goals[1,2] of and technologies for strategic defense are discussed in recent papers.[3] For the purposes of this report, the current status can be summarized by the statement that kinetic energy weapons (KEWs), because of their development, lethality, and economics, are the preferred interceptors for initial deployment. KEWs have demonstrated the ability to destroy boosters, buses, and reentry vehicles (RVs) by maneuvering into their path, colliding with them, and destroying them with hypervelocity impact. Since KEW kill packages have masses of several kilograms, the lethality of "hit to kill" is robust.

Delivering those kill packages to ranges of thousands of kilometers in hundreds of seconds means velocities of several km/s. Thus, KEWs with chemical rockets have limited ability to adapt to faster, more compact launches, which is the KEW's main limitation.[4] FELs could negate such countermeasures with their range and agility.[5] FEL technology and development are such that FELs could be ready to make that contribution when needed, and their scaling is such that an effective contribution could be made with modest platforms and constellations.

Countermeasures to KEWs include fast missiles and buses, mobile or clustered launchers, missiles that can underfly the KEWs, and antisatellite weapons (ASATs) with minimum observables that could bypass the KEWs and attack their supporting sensors. These countermeasures represent successive stages of compression of the space, time, and information that KEWs need to engage. The impact of fast burn boosters is, however, compromised by their buses' need to drift up to altitudes of 150-200 km before they can deploy decoys without their being unmasked by air drag.[6,7] That gives space-based KEWs a useful interval in which to intercept them before their missiles RVs are deployed. It also gives FELs enough time to engage them cost effectively.

II. FEL TECHNOLOGY

FELs are lasers whose operation can be described classically in terms of the radiation emitted by electrons accelerated in a magnetic field. That description gives their overall scaling, the wavelength of the light emitted when an electron beam passes through a periodic or "wiggler" magnetic field, and the losses that limit overall efficiency. Their intrinsic limits are discussed in a recent report by the American Physical Society (APS).[8] This report extends that discussion to evaluate their scaling relative to other directed energy weapons (DEWs). The technology involved is described in a companion report.[9]

A. FEL Operation

FELs use electron accelerators developed for high energy physics to produce high power laser beams through mechanisms that can be described with the theory developed for power tubes. The following paragraphs discuss their principles of operation, the components needed for high power operation, and the status of their development.

When accelerated, electrons emit radiation in a cone centered on their direction of motion. If a strong laser field with the appropriate frequency is present in that direction, the electrons are induced to radiate into--or classically, to amplify--the field. As the field absorbs this radiation, it becomes stronger.

When extraction reaches a few percent of the beam's initial energy, the electrons' motion is sufficiently distorted to inhibit further extraction. This saturation can be delayed by "tapering" the wiggler to match the wavelength of the decelerating beam, but at about 10% extraction the electron beam has been modulated as much as possible. Extraction efficiency can be improved further by passing the modulated electron beam through the accelerator backwards to produce the radio frequency (RF) field needed to accelerate the next bunch of electrons.

That could produce efficiencies of 20-40%, making power supplies a minor consideration.

FEL engineering trades accelerator complexity against optics difficulty. Converting electron beam power to laser power is most efficient if the electron beam is compressed to transverse dimensions of millimeters, but to withstand the megawatt output fluxes produced by conversion, optical components need diameters on the order of a meter to reduce the average power densities to the 10-100 W/cm^2 that their coatings can tolerate.

It is possible to extract power efficiently from a small electron beam and then expand the laser beam to sizes the optics can survive. Expansion by diffraction alone from an accelerator beam diameter d to an optic diameter D = 1 m takes a distance of about $D \cdot d/w$ for a laser wavelength w. For w = 1 μm that distance is $\approx$ 1 m$\cdot$1 mm $\div$ 1 μm $\approx$ 1 km. That is practical for ground-based FELs, but in space more compact platforms are preferred, which necessitates mirrors that can take higher fluxes. Such mirrors are now becoming available, which means that to first order, the accelerator and optical designs can be decoupled, making the construction of high energy electron and laser beams largely a matter of the parallel engineering of known designs.

B. Development

The main components of FELs are the accelerator, wiggler, optical beamline, and output mirror. Much FEL accelerator technology is common with that for neutral particle beams (NPBs). NPBs have recently demonstrated the bright current sources and efficient radio frequency quadrupoles (RFQs) needed for the low energy stages; their high energy stages have been developed for high energy physics. Their main issues are lightweighting and automatic control for space applications. FELs add only the wiggler field to convert to laser radiation. Wiggler conversion has been demonstrated at 1 micron with RF FELs and at 10 micron with induction linacs. When strongly modulated, the electron beams emit harmonics of their fundamental frequency. That limits extraction at the principal frequency and produces higher frequency radiation for which the FEL's optics are not designed, which must be suppressed to prevent damage to optical components.

For a given threat, FELs need the same size constellation as infrared chemical lasers of the same brightness, but they could produce that brightness with mirrors and lasers about a factor of 5 smaller. Initial applications could involve primary mirrors 2-4 m in diameter, for which a fabrication technology and an active industry exists. Its largest scientific project was the Hubble Space Telescope (HST), a 2.4 m near-perfect, space telescope to operate in the visible region. The HST's cost for producing, lightweighting, figuring, polishing, and coating was about $ 25 M; subsequent mirrors of that size could be produced for about $ 5 M each, which would be a small part of the current estimate of about $ 400 M for the fabrication and operation of a high brightness platform with a 4 MW laser and 4 m mirror, or "4-4" platform.[10] The APS Report inferred a much larger cost by allocating the HST's entire cost to the primary;[11] the primary's cost was actually only a few percent of the total.[12]

FELs' main advantages are their efficiency and short wavelengths. The former means that less fuel is expended per joule of laser light; the latter allows their power and mirror diameter to be reduced relative to those of other lasers. For a 4 MW FEL that was 30% efficient, the input power would be about 13 MWe, which is within the capability of existing turbines. FELs use fuels with specific energies of ≈ 5 MJ/kg, about 10 times higher than those of chemical lasers, so they could be sufficiently light and efficient for deployment in space.

III. FEL SCALING

Midcourse engagements are described elsewhere;[13] this report concentrates on boost phase intercepts, in which FELs would engage missiles and buses that are far more vulnerable than the RVs they contain and far less numerous than the decoys they would otherwise deploy later. Boost phase scaling, which is similar for all DEW concepts, is discussed in recent reports, which develop a general framework for constellation sizing.[14] The paragraphs below also study how well smaller platforms could perform in initial deployments.[15]

An essential element in determining FELs' effectiveness in boost phase engagements is estimating the number and size of defensive satellites needed to counter projected threats. While computer simulations can give the most accurate answers, analytic solutions can give significant insight into their sensitivity to the numerous parameters involved. Thus, the discussion below starts with the simplest estimates and progresses to the exact.

A. Directed Energy Weapon (DEW) Scaling

Any DEW is characterized primarily by its brightness, B, which is the product of its power, P, and mirror area, A, divided by the square of its wavelength, w, or[16]

$$B = PA/w^2. \tag{1}$$

The 20 MW infrared chemical laser-10 m mirror, or "20-10", platforms often used for scaling estimates have brightnesses of about $20\ \mathrm{MW}\cdot\pi(5\ \mathrm{m}/2.7\ \mu\mathrm{m})^2 \approx 2.2\cdot 10^{20}$ W/sr, which is roughly the brightness level required for advanced threats. A platform of brightness B produces a flux of B/r^2 on targets at range r, which would destroy targets hardened to a fluence J in a dwell time

$$t = J/[B/r^2]. \tag{2}$$

For targets at r = 1,000 km hardened to a fluence of J = 200 $\mathrm{MJ/m^2}$, that time is about $200\ \mathrm{MJ/m^2} \div [2\cdot 10^{20}\ \mathrm{W/Sr} \div (10^6 \mathrm{m})^2] \approx$ 1 s. Thus, in a 100 s engagement, i.e., the simultaneous launch of very fast missiles, each laser could destroy about 100 missiles, so to negate the simultaneous launch of 1,000 fast missiles about 10 lasers would have to be in range. The constellation would have to be 5-10 times larger, or 50-100 satellites in total, to account for the "absenteeism" of satellites that were elsewhere in their orbits at the time of launch. Early estimates gave longer kill times, but did so on the unsupportable assumption that all engagements would take place at the maximum range possible, an error that affects kill times quadratically.[17,18] The APS Report's estimate that the lasers would have to be 10 times larger resulted from the arbitrary assumption that a single laser had to engage all boosters.[19]

Refining those estimates requires a proper treatment of the interaction between the satellite and target distributions, i.e., properly averaging over the range between them and optimally allocating the lasers' fire. Several useful limiting solutions have been presented,[20] as has a near-exact, quasi-analytic solution that recovers them in the proper limits, but produces constellations that are a factor of 2-4 smaller than those from limiting solutions for large constellations of bright platforms and parameters of interest.[21] The analytic solution is much less sensitive to engagement parameters, and its results vary little with satellite altitudes $\leq$ 1-2 Mm and retarget times $\leq$ 1 s. Early concerns that the time taken to retarget could degrade performance[22] were reduced when it was recognized that the retarget angles required were a few milliradians, which didn't require moving the large primary mirrors.[23]

The exact solution is also relatively insensitive to even an order of magnitude reduction of the launch area, which usefully complements KEW's much stronger scaling of the launch area.[24] For variations about the nominal parameters above DEWs, constellations scale as[25]

$$N = K(JM/BA_LT)^{\Gamma} , \tag{3}$$

where $\Gamma \approx 0.7-0.8$. K is roughly constant, and can be evaluated

$$K = N/(JM/BA_LT)^{\Gamma} \approx 4 \cdot 10^{19} \ (m^4/sr)^{-\Gamma} \tag{4}$$

from the 47 chemical laser satellites of 20-10 performance needed for the "nominal" threat of M = 1,400 boosters hardened to J = 200 MJ/m^2 launched from an area of A_L = 10 $(Mm)^2$ and vulnerable for T = 100 s.[26] The scaling parameter JM/BAT is fundamental. If only B varies, $N \propto B^{-\Gamma}$, which means that for smaller satellites many more would be required. Initial boosters could, however, have hardnesses an order of magnitude smaller than nominal and burn times an order of magnitude larger. If so, the constellation size scales as $N \alpha (J/BT)^{\Gamma}$, so that 40-50 platforms with brightnesses 1-2% of the nominal 20-10 chemical lasers could perform useful roles against initial threats. While stated in terms of chemical lasers, this result obviously obtains for any FEL of the same brightness.

B. Brightness Scaling

The laser's brightness is given as $B = PA/w^2$ in Eq. (1), so for platform costs that vary linearly with power and aperture, or

$$C = p \cdot P + a \cdot A. \tag{5}$$

With p and a as constants, C is minimized by choosing

$$A = P \cdot p/a, \tag{6}$$

which gives the optimal power and aperture as

$$P = w(B \cdot a/p)^{1/2}, \tag{7}$$

$$A = w(B \cdot p/a)^{1/2}. \tag{8}$$

Thus, a given brightness--and effectiveness--could be attained by FELs whose power and aperture were reduced from those of infrared chemical lasers by the ratio of their wavelengths, which is a factor of 2.7 μm ÷ 0.5 μm = 5.4. A 4-4 FEL at 0.5 μm is therefore roughly equivalent in brightness and performance to a 20-10 laser at 2.7 μm.

A 4-4 FEL would also kill a hardened target in about 1 s, but the fuel required to do so at an overall efficiency of 30% would only be (4 MW·1 s) ÷ (0.3 x 5 MJ/kg) = 2.7 kg rather than the (20 MW·1 s) ÷ (0.5 MJ/kg) = 40 kg that would be required by a chemical laser. For the 10 lasers in range to kill 1,400 missiles, each would have to carry about 2.7 kg/missile·140 missiles = 0.4 metric tons of fuel, which is a negligible fraction of its overall platform mass. FELs could be made essentially inexhaustible with reasonable amounts of fuel. The electrical power needed is within the capability of existing space turbines.

C. FEL Scaling Issues

The previous section discussed the scaling of generic DEWs; this one discusses some issues unique to FELs, which suggest the development paths appropriate for them. For FELs the brightness is still $B = PA/w^2$, but for them $P = \epsilon \cdot I \cdot E$, where E is the FEL accelerator's voltage, I its current, and ϵ the efficiency of conversion from electron to laser beam energy. At high beam energies it is possible to extract energy at shorter optical wavelengths, so that $w \approx \beta/E$, where $\beta \approx 0.5\ \mu m \cdot 50$ MeV = 25 μm-MeV.[27] With this scaling the FEL brightness becomes

$$B = PA/w^2 = \epsilon IEA/(\beta/E)^2 = \epsilon IAE^3/\beta^2, \tag{9}$$

which increases as E^3 because of the E dependencies of P and w, making operation at high beam energy advantageous. Since power has significant costs, initial development could maximize $B/P \propto E^2$ by operating at high energy. Equation (9) can also be written

$$B = PA/[\beta/(P/\epsilon I)]^2 = P^3A/(\beta\epsilon I)^2, \tag{10}$$

which shows that when FELs operate in a mode limited by the maximum current the accelerator will accept, $B \propto P^3A$, which shifts the optimization of B somewhat. The optimal power-aperture relationship of Eq. (6) is changed to

$$A = P \cdot p/3a, \tag{11}$$

which means that for the same cost parameters a and p, for any given power, the optimal aperture is reduced by a factor of 3 to take advantage of the greater effectiveness of power in FELs. That limit obtains, however, for large B. For brightnesses up to those of visible 4-4 FELs, scaling and parametrics are given reasonably well by Eqs. (7)-(8).

D. Scaling Platforms of Modest Brightness

Recent discussions of scaling DEW constellations on the boost phase threat have concentrated on performance tradeoffs for large lasers and bright platforms, e.g., 20-10 chemical laser platforms. While their development is plausible and their performance and cost objectives appear favorable,[28] they require that several parameters be scaled together over significant ranges, which could require much of a decade to complete. This section explores the scaling of more modest laser constellations that might be deployed sooner, confirming the observations of the previous section that for less stressing initial threats, their performance and effectiveness could be quite favorable.

Assuming that the 4-4 FEL at 0.5 μm, which was scaled from the 20-10 chemical laser at 2.7 μm, represents a proper choice of parameters for platforms of $2.2 \cdot 10^{20}$ W/sr brightness, Eqs. (7) and (8) can be used to specify efficient platforms of lower brightness. For fixed w, P α $\sqrt{B}$ and A α $\sqrt{B}$, so that P = kA, where k is a constant, about $k = P/A = 4 \text{ MW} \div \pi(2 \text{ m})^2 \approx 0.3 \text{ MW/m}^2$. Thus, a properly matched FEL's brightness is

$$B = P \cdot A/w^2 = k \cdot A^2/w^2, \tag{12}$$

so that for any desired brightness the optimal aperture and power are given by

$$A = w(B/k)^{1/2}, \tag{13}$$

$$P = w(k \cdot B)^{1/2}. \tag{14}$$

$B = 2.2 \cdot 10^{20}$ W/sr is a long term goal, but on the way to a 4-4 platform at 0.5 μm, FEL development progressed through the near-optimal 1-2 and 2-3 combinations at 1 μm, they would have brightnesses of about $4 \cdot 10^{18}$ and $1.6 \cdot 10^{19}$ W/sr, respectively. The lower of these two brightness levels is about the level that existing, separate laboratory components might attain if they were combined. Initial development might produce such brightnesses by operating at full voltage but a fraction of the ultimate current to reduce power costs. The calculations below examine the extent to which these intermediate power levels could be of value. First, however, it is useful to estimate the costs of reduced brightness platforms.

E. Platform Costs

The costs of matched FEL platforms can be estimated from the formalism above. From Eqs. (5)-(8), for optimum P and A the total cost per platform is

$$C = 2w(a \cdot p \cdot B)^{1/2}, \tag{15}$$

which scales primarily as $w \cdot B^{1/2}$. To minimize costs, the shortest wavelength possible should be used at each step, although in practice w is set by the level of development. From the \$ 400 M estimate for investment and operating costs for a 0.5 μm 4-4 FEL, the scaled cost for an initial 1 μm 1-2 FEL should be about \$ 400 $M \cdot (1\ \mu m \div 0.5\ \mu m) \cdot (4 \cdot 10^{18}$ W/sr $\div$ $2.2 \cdot 10^{20}$ W/sr$)^{1/2} \approx$ \$ 110 M; and an intermediate 1 μm 2-3 FEL should cost about \$ 400 $M \cdot 2 \cdot (1.6/22)^{1/2} \approx$ \$ 220 M. These estimates are for the n-th platform of each kind. Initial prototypes could cost several times more, but it is the average over the constellation that matters in cost-effectiveness estimates.

The cost models discussed above assumed that costs could be allocated to variable laser, aperture, and operations cost categories. It is also possible to aggregate some of them into fixed costs of the satellite's structure, communication, and other overhead, which are significant under current practices.[29] Such fixed costs do not shift the optima in Eqs. (7)-(8), they only add a fixed cost to the right hand side of Eq. (9). That reduces the optimal brightness at cost C to

$$B = [(C-C_F)/2w]^2/ap, \tag{16}$$

which could represent a significant reduction for some small platforms. For FELs, the main costs can be traced to elements of the accelerators, converters, and beam directors, which vary directly with power and aperture, so their use above as the basis for aggregation is appropriate.

IV. SCALING RESULTS

This section presents the constellation sizes and costs that are optimal for the scaling results discussed in previous sections, concluding that while platforms of high brightness are required for ultimate, stressing applications, platforms of moderate or intermediate capability developed along the way could provide significant interim capabilities.

A. Results

The attached figures show the constellation sizes required to meet various threats, which were generated with the near-exact analytic solution for boost phase scaling discussed earlier for using the initial, intermediate, and long term brightnesses derived in the previous section. Figure 1 gives the required constellation size, N, as a function of the number of missiles in the threat, M, for these three brightnesses. The top curve is for the initial $4 \cdot 10^{18}$ W/sr; the middle is for the intermediate $1.6 \cdot 10^{19}$ W/sr; and the bottom curve is for the nominal $2.2 \cdot 10^{20}$ W/sr studied previously.[30] For 1000 missiles they give constellations of 1700, 440, and 46 satellites, respectively; and for 100 missiles they give constellations of 175, 55, and 8 satellites. That roughly bounds projected near to mid term threats.

For the latter threat, the two lower curves scale approximately as $M^{0.7-0.8}$ in accord with Eq. (3). The top curve for the lowest brightness is essentially linear in M. The bottom curve shows that only 10-40 high brightness platforms is needed for this range of threats. The middle curve shows that about 60-400 medium brightness platforms would be needed. The top curve shows that a large number of modest platforms would be needed for a large launch of fast, hardened missiles. For small launches, however, or for the operation of FELs in conjunction with KEW platforms, about 100 such platforms could still negate about 100 missiles in even a T = 100 s engagement, which could supply the gap-filling required to maintain KEW's effectiveness during that time interval.[31] Since those initial platforms should be simpler than the brighter ones needed later, the larger numbers of FELs needed initially need not be disqualifying.

Figure 2 shows the costs of the various constellations, which were produced by taking the constellation sizes from Fig. 1 and multiplying them by the satellite costs derived above: $ 110, 220, and 400 M for the initial, intermediate, and nominal brightnesses, respectively. For smaller launches of ≈ 100 missiles, the resulting costs are about \$ 20, 12, and 3 B for constellations of those brightnesses. Both sets of costs are competitive with those for near term kinetic energy gap fillers. For 1,000 missile launches the costs rise to \$ 190, 97, and 18 B. While the first is large, the last would be very effective, if the brighter platforms were available when needed.

The medium brightness platform costs are comparable to those of alternative approaches. Used in concert with KEW they would require about \$ 50 B for the strong suppression of a full launch. Thus, intermediate levels of technology, which might be available 5-10 years earlier than that of the high brightness platforms, might be deployed as an interim measure without excessive penalty. That might not be the case for the low brightness combination in the top curve, for which the total costs could be \$ 90-100 B even as a gap filler.

The dashed line in Fig. 2 is the estimated cost of the offensive missiles. Survivable offensive missiles cost about \$ 100-200 M;[32] the dashed line is based on \$ 200 M investment plus life cycle operating costs, which the the basis comparable to that used for the FEL curves. All three defensive constellations' costs are below those of the offense, although the margin in the case of modest FELs is too small to be reliable.

Cost exchange ratios are also of interest, although only rough estimates are possible at the current stage of development. If satellites of $2.2 \cdot 10^{20}$ W/sr brightness could be built and operated for the \$ 400 M estimated, the average cost exchange ratio for the bright platforms against large threats would be

$$\text{CER} \approx 1000 \text{ msl} \cdot \$\, 200 \text{ M/msl} \div 45 \text{ sat} \cdot \$\, 400 \text{ M/sat} \approx 11{:}1 \quad (17)$$

in favor of the defense. That would give reasonable cost effectiveness and some margin against offensive countermeasures. For the intermediate platforms, the margin would be more like 2:1. For low brightness it would be roughly a draw. Thus, space laser platforms with performance levels within reach of those already demonstrated could provide capable defenses against significant intermediate threats.

B. Sensitivity

The calculations above used varying numbers of missiles in the threat. For each calculation even early missiles were assumed to have the most stressing performance the offense could ultimately provide. Missiles were assumed to be hardened to the limiting value that is postulated by critics of boost phase defense,[33] and given the shortest burn and deployment times consistent with the deployment of useful decoys.[34] Existing missiles actually have engagement times of about T = 600 s rather than the 100 s assumed, which reduces satellite numbers and costs further.

Figure 3 shows the sensitivity to engagement time for launches of 300 fully hardened missiles. For bright platforms the required constellations drop from 17 to 5 platforms as T increases from 100 to 600 s, the booster burn plus bus deployment time of current missiles. Constellation sizes fall roughly as $T^{-0.7}$, so these calculations are defense conservative in light of actual deployment times and the difficulty and cost of decreasing them. Intermediate constellations drop from 135 satellites at 100 s to about 30 at 600 s. Even modest platforms drop from 500 to under 100, a significant improvement.

Figures 1-3 assume a hardening of 200 MJ/cm^2, which is thought to be limiting and to which results are quite sensitive. Near-term missiles, which are not intentionally hardened, could be an order of magnitude softer than the values assumed. Figure 4 shows the number of medium and modest satellites needed to meet the launch of 300 missiles vulnerable for 300 s as a function of their hardness, J. At full hardness, medium brightness would require about 55 satellites. For a hardness 1/10th as great, still higher than many current missiles, the number would drop to about 10 satellites. Small platforms would drop from about

175 to 30 satellites. The number of satellites and the cost of their constellations would be be reduced roughly as $J^{-0.8}$.

Further retrofit hardening would involve significant payload penalties.[35] Reductions in launch area, the only other variable of significance, would involve significant penalties to the attacker, impacting the vulnerability, penetrativity, and flexibility of the attack.[36] It would in any case produce a modest reduction in the FEL's cost exchange ratio. The reduction is under a factor of 4 for large platforms; and about a factor of 2 for intermediate platforms. Launch area causes little change for small platforms.[37]

C. Observations

Perhaps the most interesting observation is that the brightness levels that should result from current developments in laser power and mirror fabrication are consistent with those required for near-term applications. Nominal-cost directed energy platforms could support cost-effective operation. The constellations required would be significantly, but not prohibitively, larger than those required for high brightness platforms. Constellation costs could be comparable with near term kinetic energy concepts.

It is useful to note that for near-term threats, the costs for medium brightness platforms are not much greater than those for high brightness. While low brightness platforms are most sensitive to cost-brightness relationships, uncertainties in them are such that if the actual scaling of cost on brightness turned out to be stronger than that assumed, the costs of low brightness combinations could be comparable with those for the medium and high brightness concepts.[38]

V. GROUND-BASED FELs

FELs can be based on the ground, i.e., the lasers could be left on the ground and used to generate power for "fighting mirrors" in space. For boost phase engagements the FEL's power would then have to be transmitted from where it was generated to targets on the other side of the earth, which requires that the beam be transmitted up through the atmosphere, reflected by an overhead mirror to another mirror over the launch area, and redirected to the targets.

Short wavelength lasers minimize the sizes of the space mirrors required, but the main advantage of this hybrid ground basing is leaving the lasers on the ground where they can be built and maintained simply and cheaply. Leaving the lasers and their fuel on the ground minimizes the weight in orbit and makes the lasers essentially inexhaustible. Ground-based FELs could have hardnesses much greater than those of value targets, approaching those of other military targets, so they should be able to defend themselves adequately to extract a commensurate price from the attacker.

A. Scaling of Ground-Based FELs

In this hybrid mode the FELs' electrical efficiency and weight advantages are less significant than their scaling and propagation. The constellation would still require about the same number of fighting mirrors to engage the targets as would be required for space-based FELs. For visible 4-4 FELs, the results of the previous sections still apply, showing that the total number of fighting mirrors is about 50. Each of the roughly 10 fighting mirrors in the engagement would have to be provided with about 4 MW of power to negate the launch.

If each FEL provided power to one fighting mirror, the power required from it would be about 16 MW, if a conservative estimate of a factor of four is used for the transmission loss from the laser to the mirror engaged.[39] Earlier estimates that ground-based FELs "should produce an average power level of at least 1 GW,"[40] were overestimates by about a factor of 1 GW/16 MW ≈ 63, which resulted from incorrectly scaling the power needed from each laser and assuming that one laser would have to engage the whole launch. Thus, the total transmitted power is about $4 \cdot 4$ MW$\cdot$10 FEL $\approx$ 160 MW.

The factor of 4 transmission loss is adjustable. Linear propagation losses are a 10-20% effect; nonlinear effects have not been quantified. The main loss is spillage. If power is cheap it is appropriate to reduce mirror sizes, "spill power," and make it up with larger, cheap lasers. Losses could then approach a factor of 10. Over the last decade, that approach has been preferred, since ground segment costs were thought to be small compared to those of the space segments. Power was viewed as "free" compared to space mirrors, which was the fundamental motivation for leaving the lasers on the ground in the first place. The mirror size is, however, an adjustable parameter, so losses can be made as small as desired at the cost of larger mirrors and more mass in space, which is the appropriate adjustment if laser power becomes a concern. These arguments are relatively insensitive to whether the operating wavelength is 0.5 or 1 μm, that only rescales the mirrors by a factor of 2. It leaves the number of relay and fighting mirrors unchanged. In particular, it does not change the power, which is the principal quantity under discussion.

B. Propagation

Propagation involves a few main issues that need to be confirmed experimentally. There are questions about the uplink, propagation from the ground-based FEL to the redirecting mirror, and the downlink from the redirecting mirror to the target. For the latter, if the target is several tens of kilometers above the ground, the beam essentially propagates in a vacuum, and there is little problem. If, however, the target is at a lower altitude, the fluxes required to kill missiles could reach thresholds for stimulated Raman scattering, which could shift the beam's frequency and defocus it. Remaining below these thresholds would increase irradiation times. If engagements were limited to

≥ 20-30 km, it would represent a more stringent limit than that set by target cloud cover.

Uplink also involves serious concerns. There are two main issues: turbulence correction and thermal blooming. The former involves active compensation of the random disturbances due to turbulence in the air the beam propagates through. Turbulence correction has been demonstrated, and with practical numbers of active elements. Turbulence produces dynamic phase distortions over transverse length scales of r_0 = 5-10 cm. A transmitting mirror of diameter D ≈ 5 m thus requires about $(D/r_0)^2 \approx (5 \text{ m}/5 \text{ cm})^2 \approx 10^4$ actuators to correct apertures of interest, a number that is within an order of magnitude of that already demonstrated. The atmosphere must be sensed and the actuators controlled at the kilohertz rates at which the atmosphere changes, but the phase corrections are relatively local, so computations grows only as the number of actuators. The computers for correction could be a matter of replication.

Thermal blooming, the expansion of air that is heated by absorbing some of the laser beam, has also been observed and corrected. Theoretically, however, correcting turbulence in the presence of thermal blooming could give rise to an instability. The interaction is currently understood at the level of linear dispersion relations and code calculations, which predict practical solutions with penalties of under a factor of two. The prediction of its evolution into the nonlinear regime of interest involves numerical difficulties, so the issue may have be resolved experimentally. If results were unfavorable, they could impose significant constraints on ground-based FELs.

The uplink must be cloud free. While a 99.7% probability can be achieved by increasing the number of sites by about a factor of 5,[41] fewer sites would be needed if it was possible to clear holes in clouds. Most clouds are thin, and the energy required to clear a path through them small. A cloud 1 km thick with 10^{-7} g/cm^3 of liquid could be penetrated with about

1 km 10^{-7} g/cm$^3 \cdot$1 kJ/g $\approx$ 10 J/cm^2, which would require about 1 MJ for a 3 m diameter uplink beam. Because the clouds are nearby, the lasers for clearing them would not need high quality optical beams; they could be simple lasers built for that task and colocated with the high power lasers. Infrared lasers, which appear appropriate on the basis of their efficiency, absorption to scatter ratio, and reduced optical tolerances, could be much less expensive than the lasers for weapons or discrimination.

C. Space-Ground Tradeoffs

If laser power was more expensive than satellites, it would be appropriate to oversize redirection mirrors by factors of 2-3 and reduce relay losses to tens of a percent. In that case, however, ground-based lasers would actually no longer provide much leverage, so the lasers should probably be deployed in space or replaced with other concepts. That does not, however, appear to be necessary. Power on the ground does not appear to be nearly as expensive as large optics in space, absent large, uncorrectable losses.

For the range of transmission factors discussed above, each ground-based laser would need to transmit (2-10)$\cdot$4 MW $\approx$ 8-40 MW; for 10 separate ground-based lasers the total would be 80-400 MW. The total power required is the same for ground-based lasers of any size, because it is set by the threat. For small units the total power matters less than the 4-10 MW each unit must provide. Powered separately, operated independently, and constructed in a modular manner, the smaller units should also be more survivable, a significant advantage. For smaller FELs, power could be generated by peaking turbines like those used to efficiently augment electrical baseload. Power estimates of GW are misguided as well as unnecessary. If the concern is that the ground-based FELs are too big, the proper response is to scale the lasers to the smallest level possible, as done above and elsewhere.[42] The lesson from nuclear commercial power generators is that the lasers should probably be small for reliability in any case.

The fundamental arguments for ground basing are cost and inexhaustibility, although for FELs the latter is less of an issue. The arguments for space basing are efficiency and freedom from propagation constraints. Space basing would ultimately involve 8-10 visible 4-4 FELs in the battle and ≈ 30-50 altogether, accounting for absenteeism. Ground-based FELs would involve 8-10 active lasers, each of which would have a factor of 2-10 power loss, or 8-40 MW lasers. Each would have an additional factor of 3-5 redundancy for line of sight. Thus, the ratio of ground to space power would be about

$$(G/S)_P = (2\text{-}10)\cdot(3\text{-}5)\cdot 10 \div (30\text{-}50) \approx 1\text{-}20, \tag{18}$$

so that total installed power generally favors space basing. The variances are so large, particularly in the ground basing estimate, it would be difficult to argue for ground basing from a bulk power standpoint.

The fundamental quantity is, however, cost. Currently the costs for space hardware are about 100 times those for ground lasers, although that ratio might come down to about 10 with greater volume. Thus, the ratio of costs is about

$$(G/S)_C \approx (1\text{-}20)/(10\text{-}100) \approx 0.01\text{-}2, \tag{19}$$

for which the variance is worse than that for power. If the penalties for ground basing were low and the costs for space hardware were high, the decision would strongly favor ground basing. If, however, the transmission losses for ground basing were unexpectedly high and the costs for space deployment were as estimated, there would be a factor of two or more advantage for space basing. This comparison does not rule out either; data at scale will be needed to determine cost and performance. The comparison also omits several factors. Ground-based FELs would have not only the same number of small relay mirrors as the space platforms, but also a smaller number of larger relay mirrors, whose inclusion could shift the results by a factor of two towards space basing. Survivability is also a concern, although it is not yet clear which basing it would favor.

VI. SUMMARY AND CONCLUSIONS

This report has given a survey of the main issues that determine the usefulness of FELs for strategic defense. It reviewed the physics of operation, scaling to strategic applications, key components, and their current status. The main scaling results for DEW platforms were reviewed, as were the issues specific to FELs. Cost estimates were carried out for both large nominal platforms and for the more modest capabilities that might be developed along the way. Scaling with the threat, platform costs, engagement time, and target hardness were evaluated and found to vary in accordance with earlier results.

The main observation is that the FELs, which are the goals of current efforts, could apparently be useful for initial and ultimate strategic applications. Attainable technology could provide a useful capability against the countermeasures that could otherwise undermine the effectiveness of an early KEW deployment. Those FEL technologies could arguably be made available in time to meet those offensive countermeasures.

In the evaluation of alternative basings, space basing has an intrinsic advantage of about an order of magnitude in the efficiency of the use of its total installed power, but it also has current costs that could more than offset those advantages. Whether space or ground basing is ultimately superior depends primarily on unresolved transmission losses and platform costs.

The factors considered here indicate that there is a reasonable expectation that current lines of development could over the next decade lead to the development of FEL of the power and brightness levels required for significant applications in strategic defense.

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FIGURE CAPTIONS

Fig. 1. Boost phase constellations vs threat for FELs with low (L), medium (M), and high (H) brightness of $4 \cdot 10^{18}$, $1.6 \cdot 10^{19}$, and $2.2 \cdot 10^{20}$ W/sr, respectively, against missiles hardened to 200 MJ/cm^2 and vulnerable for 100 s.

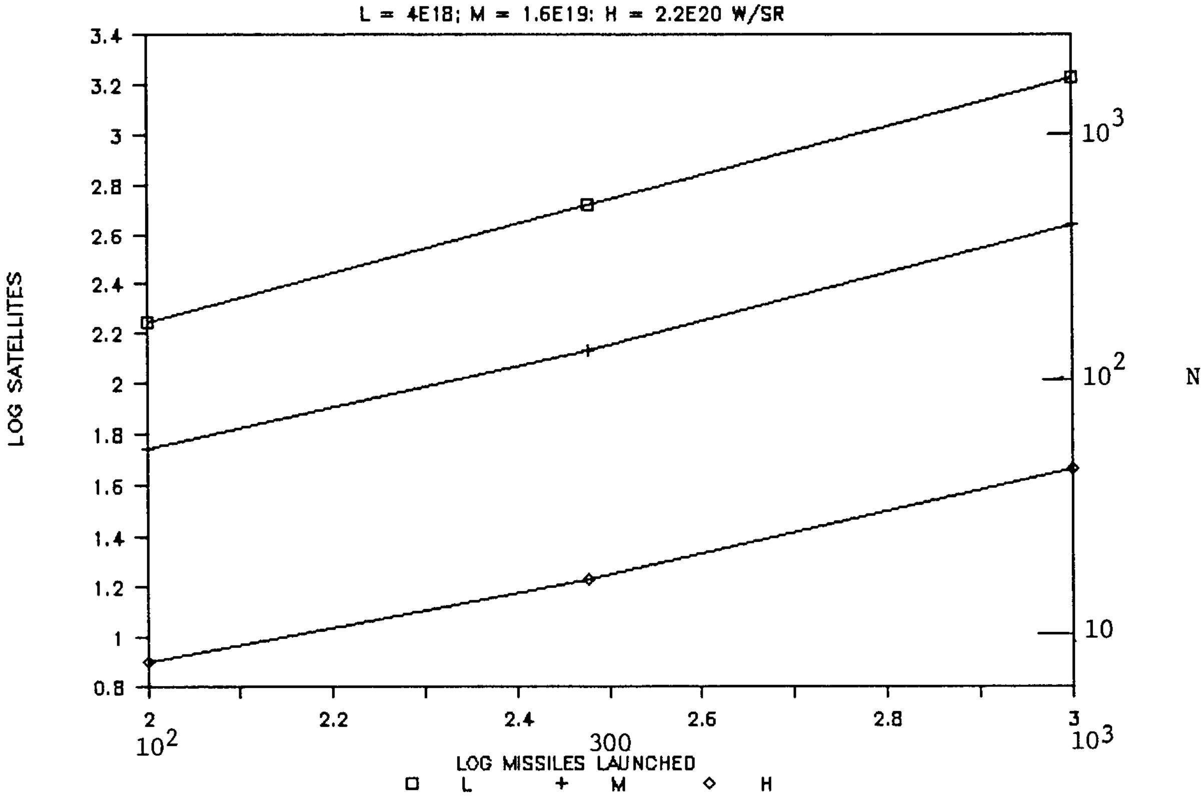
Fig. 2. Boost phase constellation costs for low, medium, and high brightness FELs and missiles hardened to 200 MJ/cm^2, launched from the current launch area of 10 Mm^2, and vulnerable for 300 s.

Fig. 3. Constellation size vs engagement time for 300 missiles hardened to 200 MJ/cm^2.

Fig. 4. Constellations vs target hardness for 300 missiles launched from 10 Mm^2 and vulnerable for 300 s.

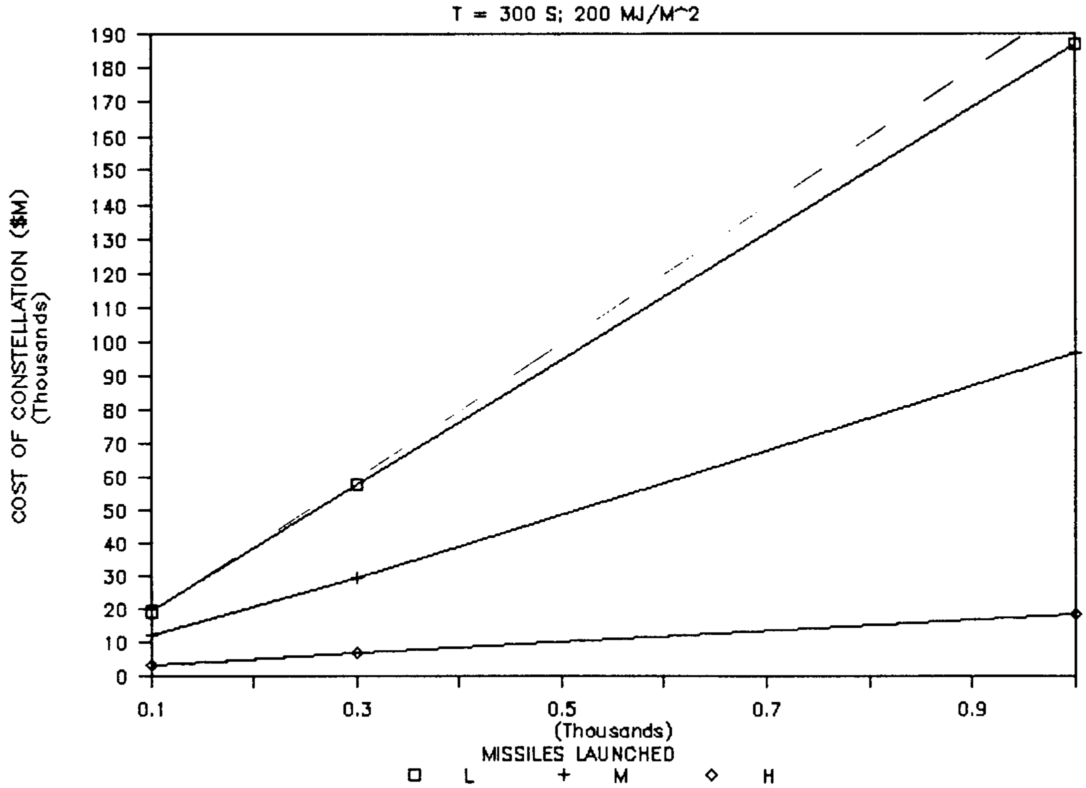
1. BOOST PHASE CONSTELLATIONS VS THREAT

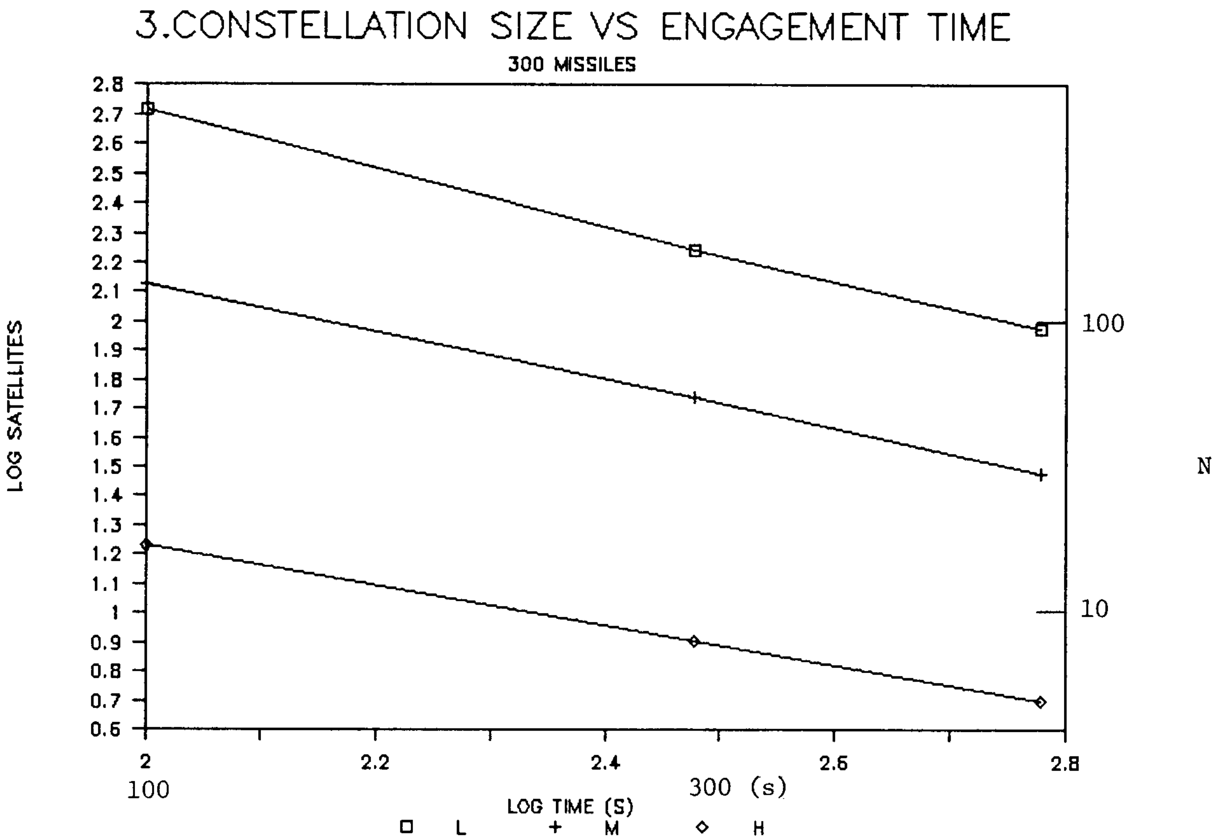
L = 4E18; M = 1.6E19; H = 2.2E20 W/SR

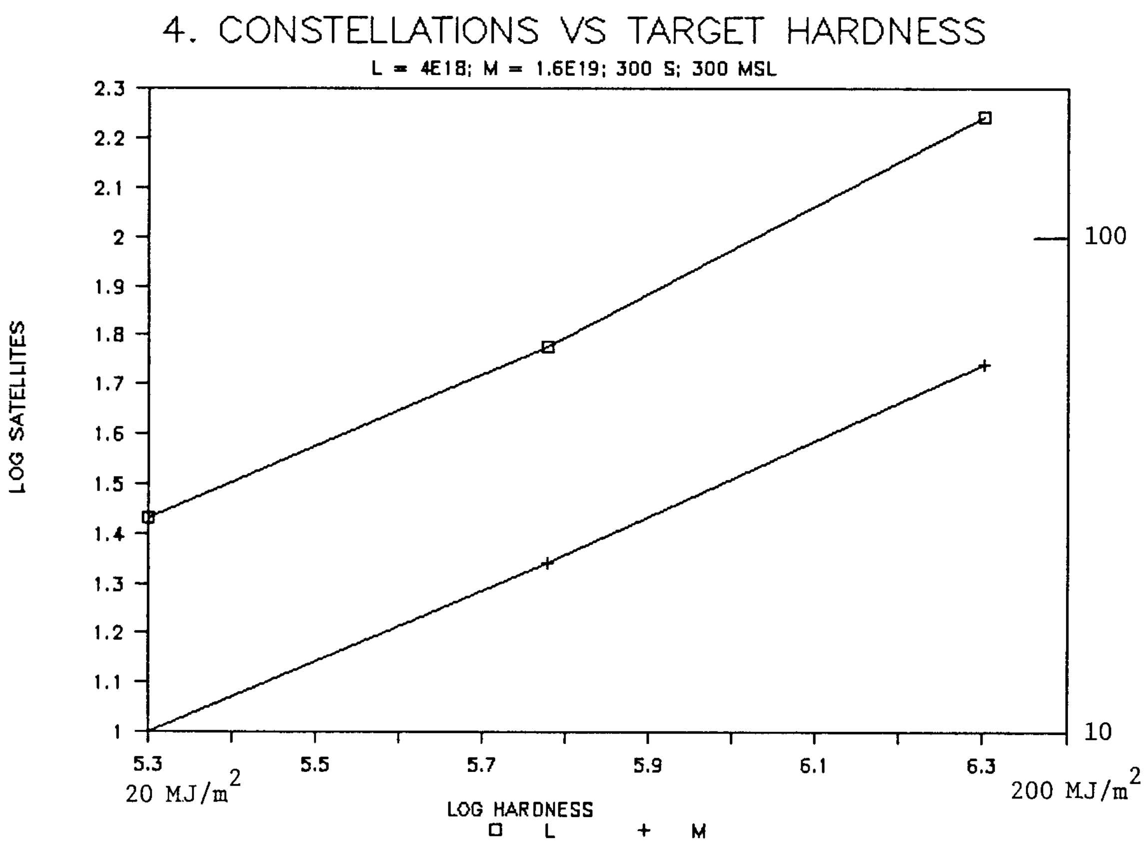


2. BOOST PHASE CONSTELLATION COSTS

T = 300 S; 200 MJ/M^2




3.CONSTELLATION SIZE VS ENGAGEMENT TIME
300 MISSILES
LOG SATELLITES
N
100
10
LOG TIME (S)
100
300 (s)
L
M
H


4. CONSTELLATIONS VS TARGET HARDNESS
L = 4E18; M = 1.6E19; 300 S; 300 MSL
LOG SATELLITES
N
100
10
LOG HARDNESS
20 MJ/m2
200 MJ/m2
L
M

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