Report to the APS of the Study Group on Science and Technology of Directed Energy Weapons

Executive Summary and Major Conclusions

The American Physical Society (APS) convened this Study Group to evaluate the status of the science and technology of directed energy weapons (DEW). The evaluation focuses on a variety of lasers and energetic particle beam technologies for their potential applications to the defense against a ballistic missile attack. This action by the APS was motivated by the divergence of views within the scientific community in the wake of President Reagan's speech on March 23, 1983, in which he called on the U.S. scientific community to develop a system that "... could intercept and destroy strategic ballistic missiles before they reach our soil...." Directed energy weapons were expected to play a crucial role in the ballistic missile defense (BMD).

The APS charged the Study Group to produce an unclassified report, which would provide the membership of the Society, other scientists and engineers, as well as a wider interested audience, with basic technological information about DEW. It is hoped that this report, detailing the current state of the art and the future potential of DEW for strategic defense purposes, will serve as a technical reference point for better-informed public discussions on issues relating to the Strategic Defense Initiative.

The study concentrated on the physical basis of high intensity lasers and energetic particle beams as well as beam control and propagation. Further, the issues of target acquisition, discrimination, beam–material interactions, lethality, power sources, and survivability were studied.

The technology of kinetic energy weapons (KEW) is not explicitly reviewed, but the role of space-based KEW in support of DEW systems is considered in the report where appropriate. Further, many important issues concerning command, control, communication, and intelligence (C^3I), computing hardware, software creation and reliability for battle management, and overall system complexity have been identified but not discussed in detail. Other issues, which were recognized but not addressed, include manpower requirements, costs and cost-effectiveness, arms control and strategic stability, and international and domestic policy implications.

DEW technology is considered in BMD applications both for midcourse discrimination between decoys and reentry vehicles, and for kill in the boost phase and the post-boost phase of ICBMs. Such consideration has become serious because of numerous technological advances during the past decade in DEW technologies. Although the achievement of an effective defense of the entire nation may require a substantial boost phase intercept component, other strategic defense scenarios, including discrimination for hard point defense purposes, would place less demanding requirements on DEW systems. The Study Group deemed it important to describe the current state of the art in DEW technology, and to evaluate it with respect to substantial boost phase intercept and midcourse discrimination roles.

Although substantial progress has been made in many technologies of DEW over the last two decades, the Study Group finds significant gaps in the scientific and engineering understanding of many issues associated with the development of these technologies. Successful resolution of these issues is critical for the extrapolation to performance levels that would be required in an effective ballistic missile defense system. At present, there is insufficient information to decide whether the required extrapolations can or cannot be achieved. Most crucial elements required for a DEW system need improvements of several orders of magnitude. Because the elements are inter-related, the improvements must be achieved in a mutually consistent manner. We estimate that even in the best of circumstances, a decade or more of intensive research would be required to provide the technical knowledge needed for an informed decision about the potential effectiveness and survivability of direct-

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Scope of the DEW study

The following was included in the APS proposal for grants from the Carnegie Corporation and the John D. and Catherine MacArthur Foundation.

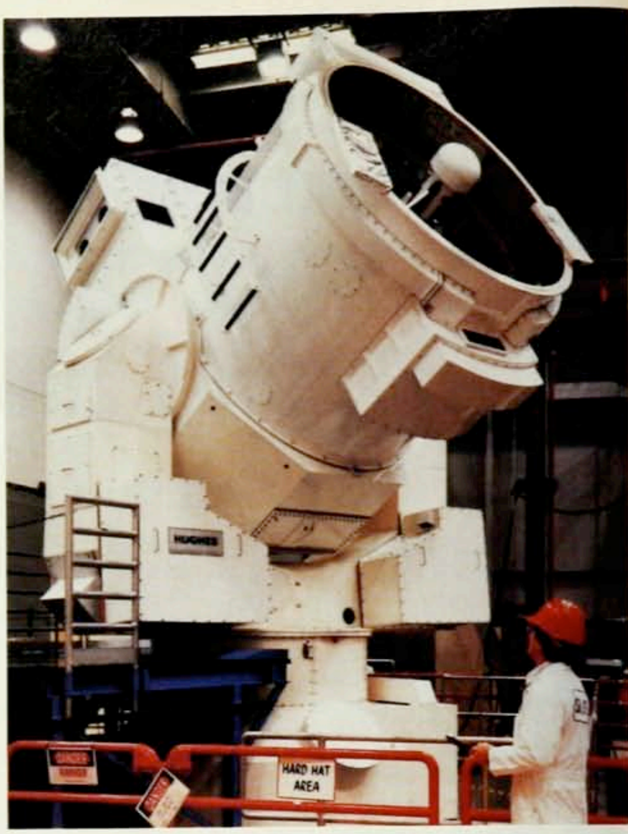
The study will review and evaluate the scientific and technological foundations of directed-energy weapons based on high-intensity laser beams of several types (the characteristics and effects of x-ray lasers will be included, but no attempt will be made to evaluate pumping by small nuclear explosions, an inherently classified subject) or on high-intensity charged and neutral particle beams. Selected aspects of projectile (pellet) approaches also will be examined for comparison. The study will emphasize technologies suitable against targets at long range, in other words thousands of kilometers.

The work will address two main areas:

▶ The physical basis of high-intensity laser and particle beams and the interactions that can affect beam control and target vulnerability. Representative topics include high-intensity beam production, beam instabilities and spreading mechanisms, long-range beam propagation and focusing, and interaction of beams with gaseous and solid matter. The study will emphasize current understanding of the underlying science, identifying physical questions that remain unclarified and limitations on performance that arise from intrinsic or fundamental physical constraints.

▶ The technological feasibility of full-scale components and subsystems for space- or ground-based applications of directed-energy weapons. Representative topics include energy sources and beam generators; beam aiming and control subsystems; target acquisition, command and control subsystems; vulnerability and countermeasures; and system integration. The feasibility evaluation will emphasize prospects for the technology as it may evolve over the next decade in order to improve delivered beam intensity and deal with the limitations or vulnerability of key components. Where possible, the study will identify R&D requirements and alternatives and also point out the implications inherent in the various approaches.

Assessment of component and subsystem feasibility requires a system context. For this purpose, the system performance of the components will be estimated against representative targets, taking into account the requirements and constraints inherent in a strategic defense mission. (Pertinent issues include the scale of directed-energy systems required for coverage against ballistic missile attacks of various types, and the possible effects on surveillance and communications satellites. The study also should recognize possible technological constraints that existing treaties may impose on field testing of directed-energy systems.) No attempt will be made to evaluate any particular existing or prospective system in detail. Instead, the study will emphasize key features of components and subsystems that govern system practicality, including order-of-magnitude cost estimates.



Beam director for the Mid-Infrared Advanced Chemical Laser, a medium-power chemical laser now used in experimental programs at the White Sands Missile Range.

ed energy weapon systems. In addition, the important issues of overall system integration and effectiveness depend critically upon information that, to our knowledge, does not yet exist.

The following observations elaborate on the above finding.

We estimate that all existing candidates for directed energy weapons (DEWs) require two or more orders of magnitude (powers of 10) improvements in power output and beam quality before they may be seriously considered for application in ballistic missile defense systems. In addition, many supporting technologies such as space power, beam control and delivery, sensing, tracking, and discrimination need similar improvements over current performance levels before DEWs could be considered for use against ballistic missiles.

Directed energy weapon candidates are currently in varied states of development. Among the many possibilities, infrared chemical lasers have been under study for the longest period and several high power laboratory models have been built. However, because of their long wavelengths and other technical features, these lasers are perceived to be less attractive candidates for BMD weapons even though they are closest to the required performance levels in a relative sense. Free electron lasers and excimer lasers are currently perceived as more attractive candidates for BMD missions; but few high power laboratory models have been operated, and the scaling required to reach relevant power levels is estimated to be greater than that for chemical lasers. Nuclear-explosion-pumped X-ray lasers, although the subject of much public discussion, are currently under study at the research level. In our opinion their BMD potential is uncertain.[1] Charged and neutral particle beam devices build on an existing base of accelerator technology but require considerable extrapolations beyond current performance levels.

Supporting technologies are also in varied states of development. In many areas, research is progressing at a rapid pace, for example schemes for rapid steering of optical beams, and active systems for tracking to microradian class or better.[2] Other critical technologies, such as the techniques for interactive discrimination, are being conceived and addressed. The same cau-

High-power chemical laser battle station in a low Earth orbit is portrayed in this artist's conception. Their comparatively compact power sources make chemical lasers favorable for space basing. Their long wavelengths necessitate using large optics over very long ranges. Atmospheric absorption makes these lasers unsuitable for ground basing.

tion described above for DEWs applies here; namely, proposed supporting technologies need to be systematically studied before their performance at parameter levels appropriate to BMD applications can be realistically evaluated.

Like any defensive system an effective DEW defensive system must be able to handle an evolving and unpredictable missile threat. In addition to retrofit and redesign of the missiles themselves, decoys and other effective penetration aids can be developed by the offense over the long times required to develop and deploy ballistic missile defenses. In contrast to the technical problems faced in developing DEWs capable of boost phase kill for defense systems, the options available to the offense, including attacks on DEW platforms, may be less difficult and costly to develop and may require fewer orders-of-magnitude performance improvements.

A successful BMD system must survive, but survival of high value space-based assets is problematic. Ground-based assets of DEW systems are also subject to threats. Architectures which address the responsive threat are still in their infancy. As an overall BMD system employing directed energy weapons becomes more complex, the currently unresolved issues of computability, testability, and predictability become increasingly critical.

For directed energy weapons to have an important role as a kill mechanism in a strategic defense system, designed to defend the entire nation against a ballistic missile attack, the following requirements need to be met:

I. For operations in the boost phase:

A. Sufficient power/energy from the directed energy weapons to kill the ballistic missile in the boost phase, or to kill the post-boost vehicle during the deployment phase.

B. Sufficient beam quality, pointing accuracy, and agility (retargetability) to deliver lethal powers or energies to targets within the available engagement time provided by the system.

C. For lasers, optical systems for transmitting beams from sources to targets.

D. Accurate detection, location of the booster in its plume, and precision tracking from launch detection until kill is accomplished.

E. Reliable kill verification.

II. For operations during the midcourse:

A. Reliable means of discrimination between reentry vehicles and decoys unless all objects can be destroyed.

B. Accurate detection, tracking of a very large number of objects in the midcourse flight, and kill verification.

C. Rapid retargeting and sufficient delivered power/energy from the DEW to destroy the reentry vehicles.

III. For terminal phase:

We do not expect DEW to play an important role in the terminal phase of the trajectory of ballistic missiles.

IV. For space-based operation:

A. Nuclear reactors or other means to supply adequate electrical power for housekeeping functions.

B. Adequate burst power for operation of DEW during engagements.

C. Space qualified reliability of all components and subsystems on the platform notwithstanding long periods of dormancy.

How leading candidate DEW sources work

Chemical lasers (see the figures on pages S4 and S5) operate by using an exothermic chemical reaction to pump the molecular vibration level, which lases. Typically, separate oxidizer and fuel streams are rapidly mixed inside an optical cavity. For instance, in the HF laser a combuster is used to produce atomic fluorine, F, which then reacts with molecular hydrogen, H_2, to produce the upper laser level, vibrationally excited HF.

To make an **excimer laser** (see the figures on page S7), one uses an electron beam or a gas discharge to produce excitations or ionizations from electron impact in a gas. These excitations or ionizations cause a chain of chemical reactions that results in an excited molecule whose ground state is either repulsive or very weakly bound. Thus, in an excimer species every upper-state molecule formed is, effectively, a population inversion. One family of excimers, rare-gas monohalide molecules (such as KrF and XeCl), produces radiation in the soft uv (249 nm for KrF, 308 nm for XeCl) at relatively high efficiencies (2–7% overall), and is of principal interest for weapons applications. Individual laser cavities use unstable resonators to extract high power without optical damage.

A **free electron laser** (see the figures on pages S10 and S11) operates by sending an intense, energetic electron beam through an undulating magnetic field to produce coherent radiation. The "extraction efficiency" of an FEL is the transfer of beam power to electromagnetic wave power. The high-energy electron beams of FELs can be produced either by accelerating electrons in rf cavities (as is done in most conventional particle accelerators) or by passing them through linear acceleration stages in which the beam acts, in essence, as the secondary to a series of primary transformer windings. The accelerators are known as rf linacs and induction linacs, respectively, and the same nomenclature applies to the FELs themselves. Because they have relatively lower acceleration gradients, induction accelerators must be very long (hundreds of meters for electrons with energies of hundreds of MeV), too long to make them practical as laser oscillators; rf FELs can be operated either as oscillators or as amplifiers, but high-energy oscillators raise questions about damage to optical components.

A **neutral-particle beam generator** (see the figures on pages S12 and S13) consists of a negative hydrogen ion (H^-) source, an rf quadrupole that provides initial acceleration and transverse focusing of the ion beam, a drift-tube linac that provides the major fraction of acceleration, a beam expander that takes the small transverse beam to a large radius (and hence very small angular divergence) and a stripper that removes one electron (but not two electrons) so as to produce neutral hydrogen, H^0. The beam must be directed and its direction sensed before the final stripping.

V. For system survivability:

A. DEW must be able to operate in a hostile environment during a conflict.

B. DEW must be integrated in an overall system that includes a survivable command, control, communication, and intelligence (C^3I) system.

We have examined most of these issues in some detail, except for items III, IV.C, and V.B. The following major conclusions are based on detailed considerations in the main body of the report indicated by relevant section numbers in parentheses.

1. **We estimate that chemical laser output powers at acceptable beam quality need to be increased by at least two orders of magnitude for HF/DF lasers for use as an effective kill weapon in the boost phase. Similarly for atomic iodine lasers, at least five orders of magnitude improvement is necessary.**

The HF/DF cw chemical lasers have been stated to yield power levels exceeding 200 kilowatt with acceptable beam quality.[3] Based on these data, we estimate that even the least demanding strategic defense applications require power levels to be increased further by at least two orders of magnitude while retaining beam quality. However, the laser geometry which achieved the above demonstration will have scaling problems to higher power levels; thus, the combination of power scaling and adequate beam quality remains an open issue. A chemically pumped atomic iodine laser at 1.3 μm has been developed, although at this point only 5 kW of continuous wave power has been demonstrated. Because of atmospheric absorption, the HF laser ($\lambda = 2.8$ μm) would have to deployed on space platforms, while the DF laser ($\lambda = 3.8$ μm) and the atomic iodine laser ($\lambda = 1.3$ μm) could also operate on the ground. When based in space, chemical lasers face a special set of problems arising from vibrations and the exhaust of the burnt fuel (Section 3.2).

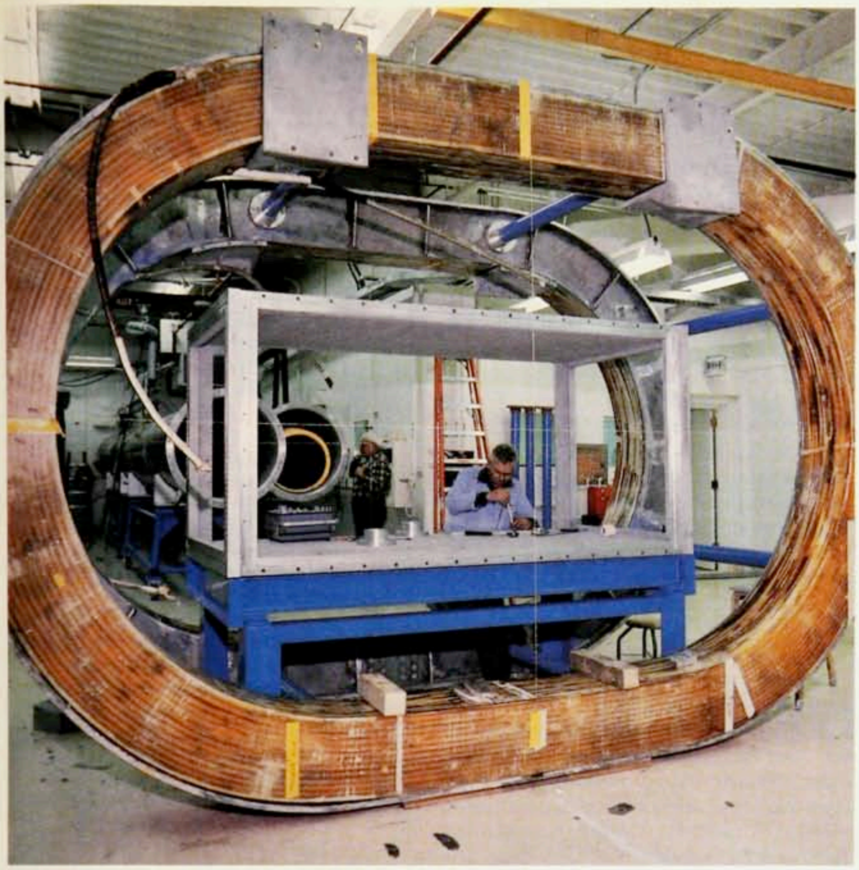
2. **We estimate that the pulse energy from excimer lasers for strategic defense applications needs improvement by at least four orders of magnitude over that currently achieved. Many advances are needed to achieve the required repetitive pulsing of these lasers at full scale.**

The pulsed excimer lasers have demonstrated single pulse energies of about 10 kJ in 1 μsec pulses from a single module[4] (Section 3.3). This laser currently uses krypton fluoride ($\lambda = 249$ nm); the other principal contender excimer species is xenon chloride ($\lambda = 308$ nm). From our estimates, assuming an overall propagation loss factor of four (relay mirror losses, Rayleigh scattering losses, and atmospheric losses), ground-based excimer lasers for strategic defense applications must produce at least 100 MJ of energy in a single pulse or pulse train with a total duration between several and several hundred microseconds (Section 6.3). To kill multiple targets a firing rate of ten per second would be desirable. For thermal kill 1 GW of average power would be required (Section 6.2). The gap of four orders of magnitude might be bridged by first combining lasers into modules at the hundreds of kilowatt level, then combining many modules optically. To produce high optical quality beams from the modules, the output from low optical quality amplifier apertures may be combined using stimulated Raman scattering or other means (Section 3.3). We estimate that the techniques for Raman beam combination must be scaled up by two orders of magnitude or more in combined laser power and efficiency from that which has been demonstrated in the laboratory. The technology for phase locking a large number of modules is not yet demonstrated (Section 5.4).

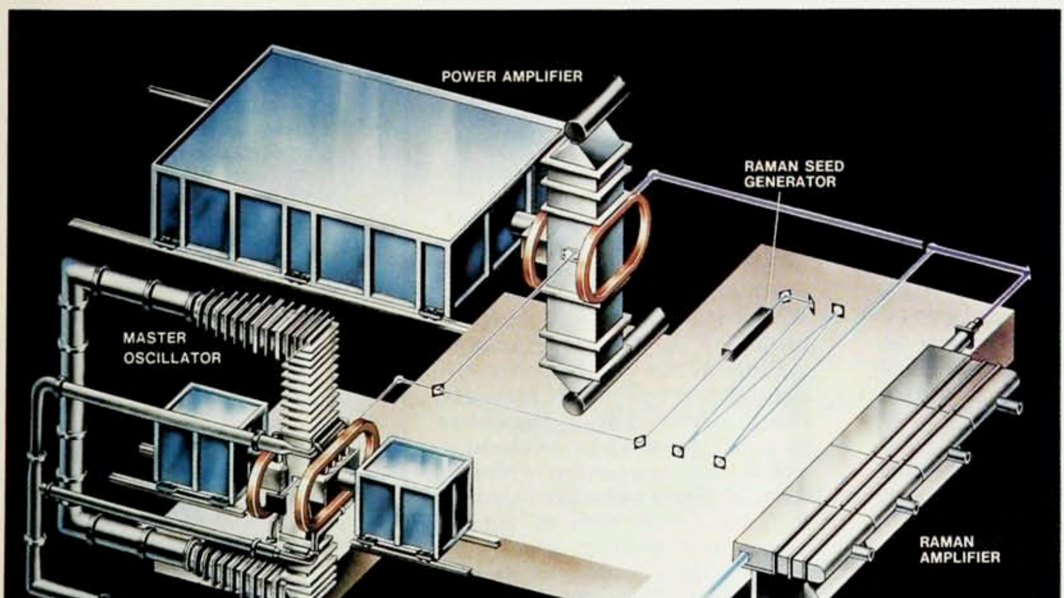
3. **Free electron lasers suitable for strategic defense applications, operating near 1 μm, require validation of several physical concepts.**

The free electron laser (FEL) is one of the newest laser technologies to be demonstrated. Peak powers of approximately 1 MW have been produced at a wavelength of 1 μm; peak powers of approximately 1 GW have been produced at a wavelength of 8 mm, demonstrating high gain and high efficiency at that wavelength.[5] Scaling to short wavelengths at high powers is a more difficult technical problem than simply increasing average power. Obtaining high efficiency, high power free electron laser operation at 1 μm requires experimental verification of physical concepts which thus far are only theoretically developed, e.g., optical guiding and transverse sextupole focusing for the amplifier configuration, and sideband and harmonic control for the oscillator configuration.[6] We estimate that for strategic defense applications, a ground-based free electron laser should produce an average power level of at least 1 GW at 1 μm wavelength, corresponding to peak powers of 0.1–1.0 TW (Sections 3.4 and 6.3).

4. **Nuclear-explosion-pumped X-**



Cavity of a large KrF laser under construction at Los Alamos National Laboratory. The large oval magnet coils provide uniform deposition of electron beam energy in the lasing gas. The laser oscillates in the left–right direction in this photo.



Artist's conception of an excimer laser facility designed to provide good beam quality by Raman cleanup, in which the output from the excimer laser pumps a Raman-active gas (hydrogen); then a seed beam with high optical quality extracts the power from the medium, shifting the wavelength of the original beam slightly and retaining the optical quality of the seed beam.

ray lasers require validation of many of the physical concepts before their application to strategic defense can be evaluated.[7]

A sub-committee of the Study Group reviewed the progress in X-ray lasers. A nuclear-explosion-pumped X-ray laser has been demonstrated. This is a research program where a lot of physics and engineering issues are still being examined. What has not been proven is whether it will be possible to make a militarily useful X-ray laser[7] (Section 3.5). Atmospheric interaction limits the use of nuclear-explosion-pumped X-ray lasers to altitudes greater than about 80 km (Section 5.10). The high energy-to-weight ratio of the nuclear explosives makes it possible for these devices to be considered for "pop-up" deployment (Section 9.3).

5. **We estimate that neutral particle beam (NPB) accelerators operating at the necessary current levels ($>$100 mA) must be scaled up by two orders of magnitude in voltage and duty cycle with no increase in normalized beam emittance. The required pointing accuracy and retargeting rate remain to be achieved. These devices must be based in space to avoid beam loss via atmospheric interactions.**

Structural kills with NPB devices require an equivalent charge of about 1 coulomb (e.g., 100 mA for 10 seconds) delivered at a few hundred MeV, with a beam divergence of 0.75–1.5 microradian (as discussed and calculated in Sections 4.3 and 6.4). Disruption of electronic function because of radiation dose could occur at significantly lower beam parameters, although this kill mechanism is system dependent, and kill assessment may be more difficult (Chapter 4).

Existing radio frequency (rf) ion accelerators have achieved particle kinetic energies of several hundred MeV, but at beam current levels two orders of magnitude below the required levels (Section 4.3). New negative ion sources have achieved the necessary peak currents and low beam emittances, but such sources have not been reported to operate continuously. Additional issues are emittance growth of the high current beams in the low energy accelerator sections, and the development of large bore magnetic optics. Power requirements and weight are also significant issues (Chapter 8).

Ionization of the neutral beam atoms via atmospheric collision (and subsequent ion deflection in earth's magnetic field) establishes a minimum operating altitude of about 120 km for beam kinetic energies of a few hundred MeV (Section 4.1).

In order to take advantage of the absentee ratio of a NPB device platform constellation designed for booster kill, NPB devices have been suggested for use in an interactive midcourse discrimination mode (identifying massive reentry vehicles in a postulated threat cloud which includes lightweight decoys). In this case the beam power requirements will not change significantly, but the target dwell times may be reduced by a factor of 10–1000, and retargeting rates of $>10\ \text{sec}^{-1}$ may be necessary. Hence, device issues which will require new ideas and further exploration for this mission are development of rapid retargeting mechanisms using magnetic beam steering and fast accurate methods for beam direction sensing (Section 7.7).

6. **Energetic electron beams require propagation in laser-created plasma channels in order to avoid beam deflection in the earth's magnetic field; this restricts the operational altitude at the low end by beam instability and at the high end by ion density starvation. We estimate that booster kill applications require a scale-up in accelerator voltage by at least one order of magnitude, in pulse duration by at least two orders of magnitude, and in average powers by at least three orders of magnitude. Active discrimination applications require scale-up in pulse duration by at least two orders of magnitude, and in average power by at least two orders of magnitude. The lasers needed for the creation of plasma channels require develop-**

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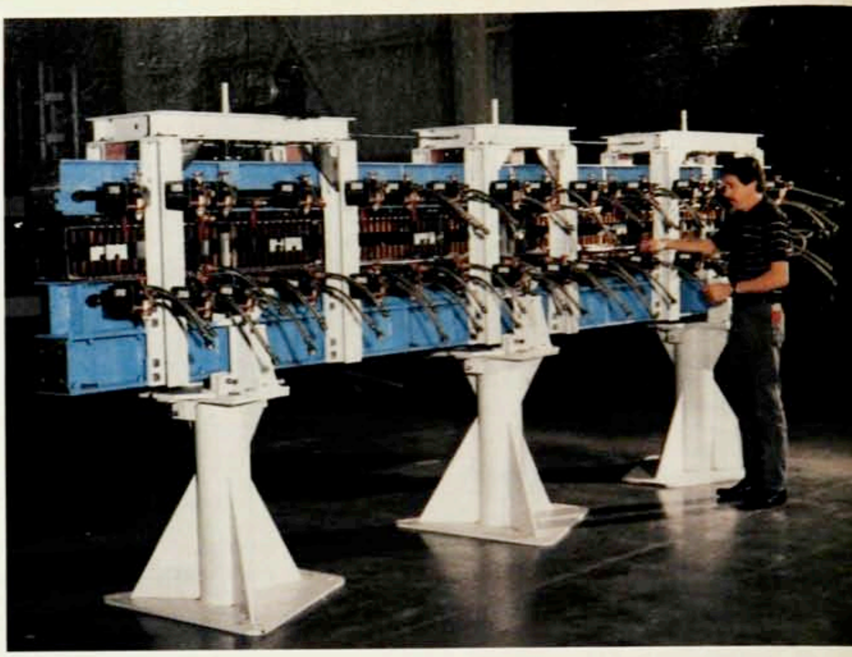


Wiggler section of a free electron laser device now operating at Los Alamos National Laboratory. An electron beam from an accelerator is guided into one end of the wiggler; as the beam propagates through the vacuum channel in the wiggler, it is subjected to magnetic fields of varying intensity perpendicular to its path. The electrons oscillate and radiate in phase as the magnetic fields accelerate them.

ment. We estimate that propagation distances must be increased by several orders of magnitude.

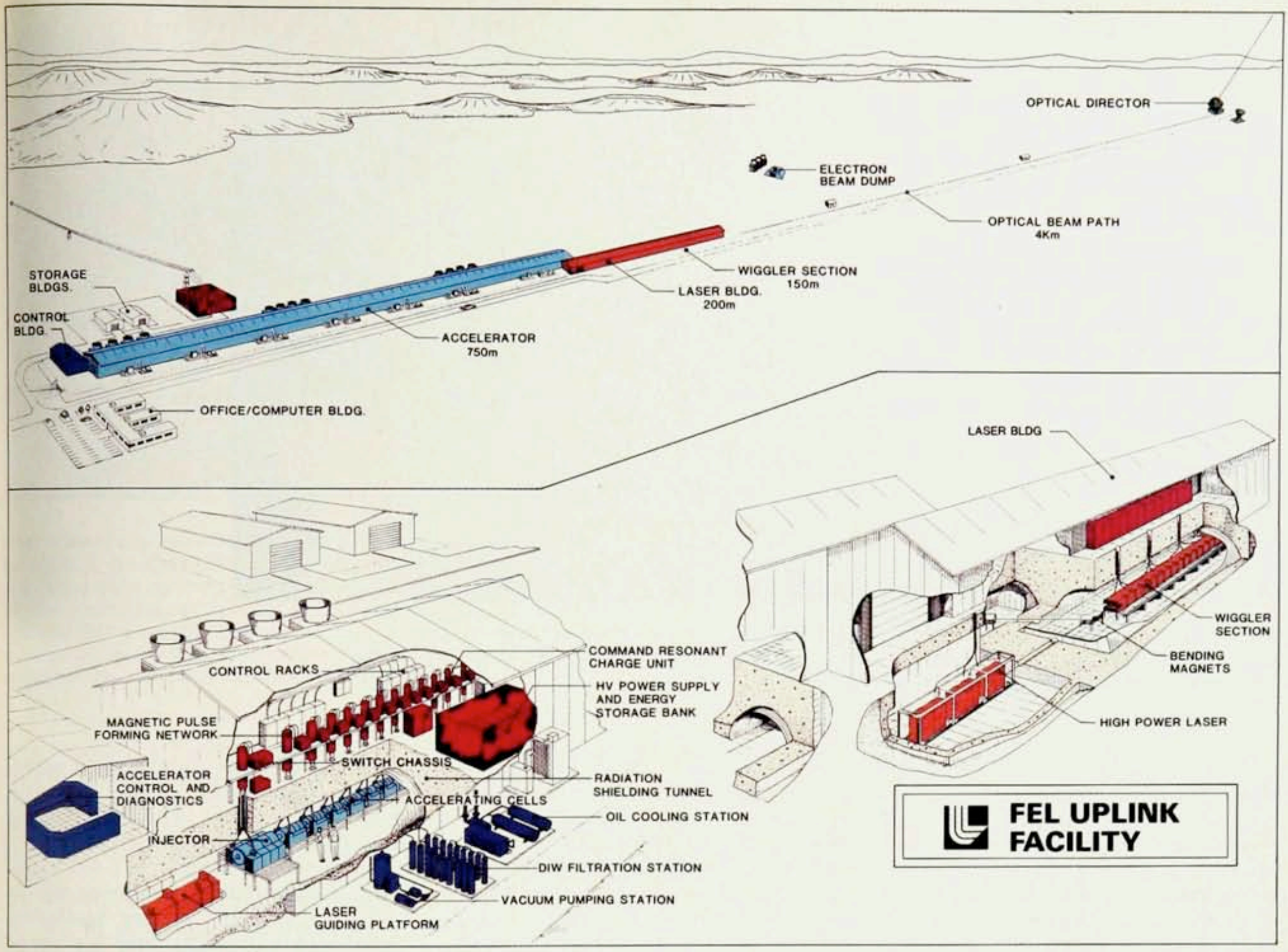
Propagation through a laser-created plasma channel is necessary to prevent beam space-charge blow-up and beam bending in the earth's magnetic field. This implies both a lower and an upper altitude operational limitations. The lower bound arises from beam stability considerations, while the upper bound results from ion density starvation. This mechanism for beam guiding has been successfully demonstrated in the laboratory, but over distances of 95 meters[8] (Section 4.2). For optimum beam currents of a few kiloamperes, delivering lethal pulses to distances in excess of 1000 kilometers will require beam kinetic energies of several hundred MeV. Useful ranges for some suggested interactive discrimination applications could be as small as a few hundred kilometers, in which case the particle energy requirement would decrease by an order of magnitude (Section 7.7). Existing linear induction accelerators have demonstrated the necessary peak power capability (tens of MeV at peak currents of tens of kiloamperes and pulse repetition rates of a few hertz), although not for required pulse lengths of microseconds (Section 4.2). Although several approaches have been suggested, the laser technologies required for creating the plasma channel have not been demonstrated. Because of the limited engagement space, rapid retargeting (~ 0.1 sec) and high repetition rates (≥ 10 Hz) are essential.

7. **Phase correction techniques are required for obtaining near diffraction limited performance of most types of laser weapon devices. Further, phase control techniques are required for coherently combining outputs from different modules in a multiple laser system into a single diffraction limited beam. These techniques, demonstrated at low powers, must be scaled up by many orders of magnitude in power.**

High power laser systems are likely to require active control and correction of the optical phase of the output beam to reach the nearly diffraction limited performance desired for strategic defense applications. Several techniques are available for these purposes. These include correction of slowly varying phase errors with low spatial frequencies through use of adaptive optics and self-correction of phase errors using nonlinear phase conjugation techniques, such as stimulated Brillouin scattering, or four-wave mixing; and combining beams from multiple apertures by phase locking of multiple laser modules, or through stimulated Raman scattering. Each of the laser technologies under development may use different types of phase corrections. All of these approaches for phase correction have been demonstrated on a laboratory scale, but extensions to high power systems and large apertures remain to be demonstrated (Section 5.4).

8. **Dynamic phasing of arrays of telescopes requires extensive development in order to obtain large effective aperture optical systems. As calculations indicate (Section 5.4.5), the number of phase correcting elements must be increased by at least two orders of magnitude over currently demonstrated values.**

Optical laser systems will require large effective optical apertures in order to achieve the necessary beam intensity on target. Such radiating apertures have to provide near diffraction limited beams which can be rapidly retargeted. The state of the art for ground-based monolithic telescope primaries for astronomical applications is about 8 meters.[9] Torque requirements for rapid steering of large telescopes limit such telescopes to approximately 8 meters aperture; the larger "effective aperture" primaries have to be synthesized by dynamically phasing a number of smaller telescopes. Such phasing of a number of telescopes has been accomplished[10] by dynamically controlling the wavefront "piston," tilt, and focus of the laser beams feeding each telescope of the array. This adds complexity to the system but allows beam pointing in terms of target tracking



Schematic of the Lawrence Livermore National Laboratory proposal for one of the two FEL approaches that are being considered for construction at White Sands Missile Range. This FEL uses an induction accelerator; the Los Alamos FEL shown on the facing page uses an rf accelerator.

without requiring slewing of telescopes (Section 5.2).

The phase front of the outgoing wave is monitored in such phasing schemes, and corrections are applied via electrically driven actuators. Components for control of about several hundred such actuators are commercially available. For the large apertures contemplated for BMD applications the number of actuators needed lies between ten thousand and one hundred thousand, a substantial extrapolation. The technology of phase-controlling an array of primary mirrors is in an early stage of development. Scaling of such arrays to high power has not been accomplished (Section 5.4).

An alternative approach is to use telescopes where the primaries are made out of single large flexible membranes which are appropriately distorted by many actuators. The concept has been demonstrated only for small flexible primaries at low powers. Extensions to large mirrors at higher powers remains to be shown (Section 5.4).

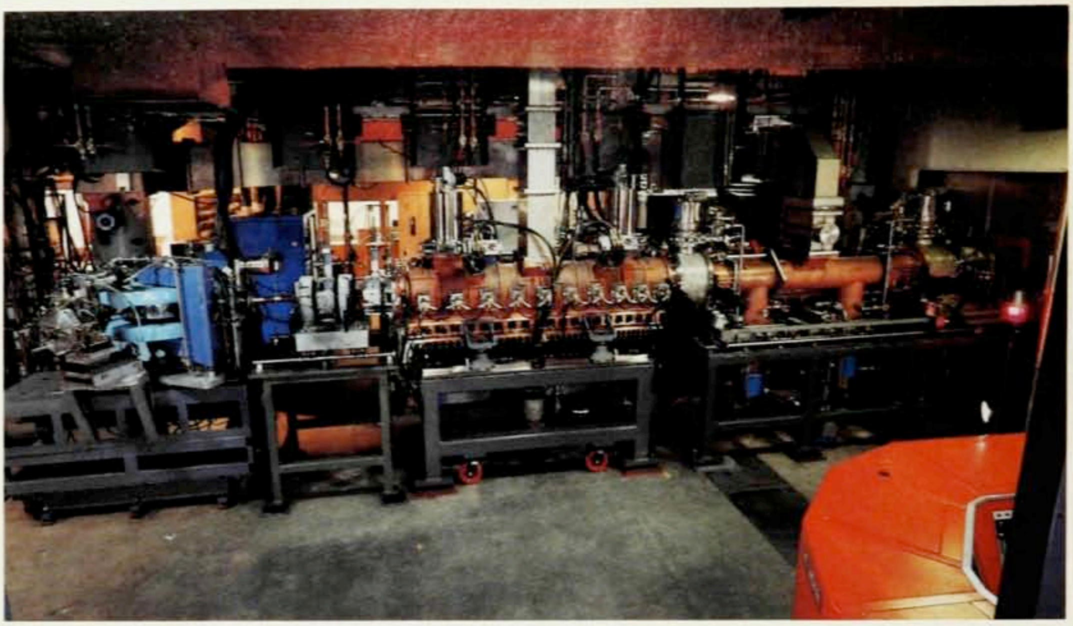
9. The optical coatings of large primary mirrors are particularly vulnerable in space-based optical subsystems.

The large primary mirror, which directs the laser beam towards the target, is particularly vulnerable to radiation from other lasers (from any direction) (Section 5.6). Based on discussions with commercial vendors, we find that the cw power loading threshold for reflective coatings is about 100 $\mathrm{kW\,cm^{-2}}$. For laser pulses of a few microseconds or less, the damage threshold will be about 8 $\mathrm{J\,cm^{-2}}$ of absorbed energies, corresponding to peak powers of 10 $\mathrm{MW\,cm^{-2}}$. These damage thresholds are for operation at a nominal laser wavelength of 3 μm (Section 6.2). If attacked by lasers at other wavelengths in the visible, near ultraviolet (UV), or X-ray region, the damage threshold may be significantly lower. Further, there is a possibility of damage to the high reflectivity coatings from energetic particles in the ambient background, i.e., MeV protons and electrons, during long term residence of the high reflectivity mirrors in space.

10. Small secondary mirrors in the optical trains of high power lasers will need very low absorptivity coatings and will have to be cooled.

The requisite power levels for ballistic missile defense lethality will necessitate cooling of the small mirrors in the optical train of high power lasers to prevent damage. A beam power of 1 GW on a mirror of 100 $\mathrm{cm^2}$ area implies an incident power of $10^7\ \mathrm{W\,cm^{-2}}$. High reflectivity coatings with less than 10^{-4} absorptivity are needed. Such mirrors have been demonstrated, and lead to an absorbed power of 1 $\mathrm{kW\,cm^{-2}}$. Cooled silicon or silicon carbide mirrors show promise for raising this threshold (Section 5.5).

11. Ground-based laser systems for BMD applications need geographical multiplicity to deal with adverse weather conditions.



Whitehorse Test Stand, an accelerator for production of neutral-particle beams at Los Alamos National Laboratory. The accelerator produces beams of negative ions, then strips the extra electrons in a gas cell, leaving a neutral beam.

For each ground-based laser system which must be available in battle, a number of geographically separated laser sites are needed to provide availability of at least one site in the system when the others are obscured by adverse climatic conditions. These locations must be separated by distances greater than the coherence length scale for weather patterns. Based on weather statistics, a multiplicity of five independent ground-based lasers could provide a 99.7 percent availability. By going to 7 climatically isolated locations in the continental U.S. availability of 99.97 percent is possible. At each of these sites, local cloud cover conditions require further multiplicity of the large ground telescopes, separated by few km (Section 5.4).

12. **Ground-based laser systems require techniques for correcting atmospheric propagation aberrations. We estimate that these techniques must be extended by at least two orders of magnitude in resolution (number of actuators) than presently demonstrated. Phase correction techniques must be demonstrated at high powers.**

Ground-based laser systems will require either linear or nonlinear adaptive optics of a very sophisticated nature in order to precompensate the laser beam for atmospheric aberrations caused by atmospheric turbulence and by thermal blooming induced by the laser beam itself. A retroreflector or a low power laser located at an appropriate point-ahead position in front of a space-based relay mirror would provide a reference source for transmission through the atmosphere to the ground telescope, where the wavefront would be analyzed for acquired aberrations due to the atmosphere. This analysis would be used to actuate adaptive optics of high resolution ($\geqslant$10,000 actuators per aperture) at high bandwidths ($\simeq$1.0 kHz). This technique requires an extensive computational capability. Such atmospheric compensation experiments have been successfully demonstrated at low powers (no thermal blooming in the atmosphere) and at average atmospheric viewing conditions for Mt. Haleakala, Maui (moderate turbulence), with a small number of actuators ($<$100). At high power levels, the turbulence may be high enough to cause a beam intensity redistribution which could be uncorrectable (Sections 5.2 and 5.4).

The incorporation of phase correction schemes in pulsed induction linac FEL amplifier is particularly stressing because the atmospheric compensation must be carried at high power levels. Atmospheric compensation techniques are needed for point-ahead angles which are large and for targets which may be non-cooperative.

13. **Uplink in a ground-based laser system faces transmission losses in the atmosphere.**

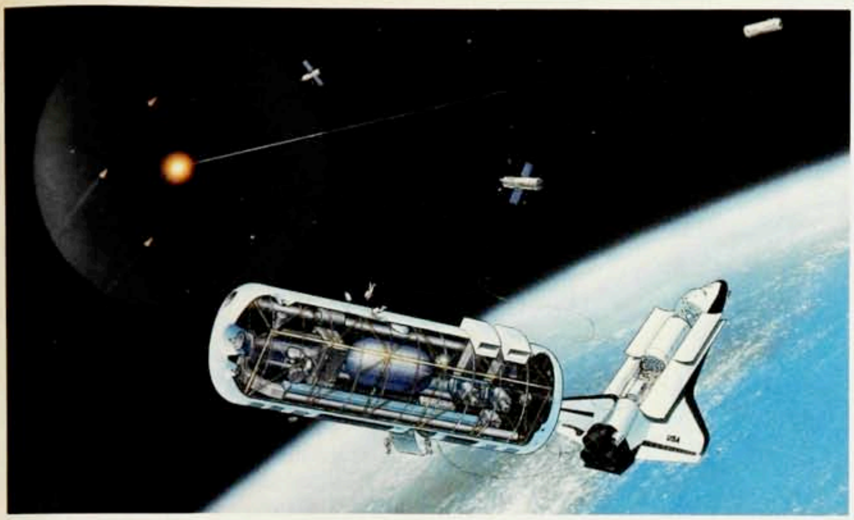
The uplink of high power output from a ground-based laser system faces natural atmospheric losses such as Rayleigh scattering, which stress the short wavelength systems, and atmospheric absorption losses, primarily from water vapor, which stress the longer wavelength systems. The optimum wavelength region is 0.4–1.0 μm. Even in this region, nonlinear effects such as stimulated Raman scattering and thermal blooming force the use of large final transmitting optics on ground (Section 5.4).

14. **Nonlinear scattering processes in the atmosphere impose a lower limit on the altitude at which targets can be attacked with a laser beam from space.**

Power delivery downward through the atmosphere to rising targets may be limited by stimulated Raman scattering and thermal blooming by ozone absorption. These phenomena limit the minimum attack altitude to 80 km for very short pulses, or require a longer pulse length (1–10 ms), because the laser beam must be focused to a small, $\sim$1 m^2, spot size on the target. At the required high laser intensities, nonlinear effects may throw the optical power out of the focused beam before reaching the target (Section 5.4).

15. **Detection and acquisition of ICBM launches will pose stringent requirements for high detection probability and low false alarm rates.**

The achievement of boost phase kill probabilities of 90% implies booster detection and acquisition probabilities of better than 90%. In addition, successful operation of a midcourse system depends importantly on being given



Deployment of a neutral-particle beam battle station in space is envisioned in this artist's conception. Neutral-particle beams cannot propagate in the atmosphere; they would be stripped and the resulting ions would be deflected by Earth's magnetic field. Unlike lasers, particle beams deposit their energy inside their targets, rather than on the surface. Low-intensity neutral-particle beams could be used to discriminate between RVs and decoys or to damage a missile's firing mechanism. High-intensity beams might, for example, cause structural failure of the RV or effectively disarm its nuclear weapon.

good booster trajectory information. Of even greater importance, low false alarm rates are required so that a BMD system is not activated in peacetime because of the false alarms (Section 7.2).

16. For boost phase, infrared tracking of missile plumes will have to be supplemented by other means to support submicroradian aiming requirements of DEWs.

Tracking of missiles by detecting the intense short wavelength infrared (SWIR) radiation from booster plumes is a technology which has been pursued for some time. The plume brightness greatly exceeds that of the missile, and the position of the missile within the plume depends in a complex manner on altitude, missile type, rocket motor, fuel characteristics, etc. and is susceptible to variation by the offense in a manner which cannot be predicted by the defense. Other passive means of accurately locating and tracking missiles in boost phase are in early stages of study (Section 7.5).

Active means of tracking may be required. Of the likely candidates, microwave radars are the most developed although electronic countermeasures for them are also well developed. Optical radars may be more promising, if the illuminating beam can be rapidly retargeted, and if an imaging capability can be achieved (either range–Doppler or angle–angle systems would be sufficient). If rapid retargeting cannot be developed and if power–aperture requirements for microwave radars become too severe hundreds to thousands of space platforms will be needed (Section 7.6).

17. For post-boost and midcourse, precision tracking will require active sensor systems.

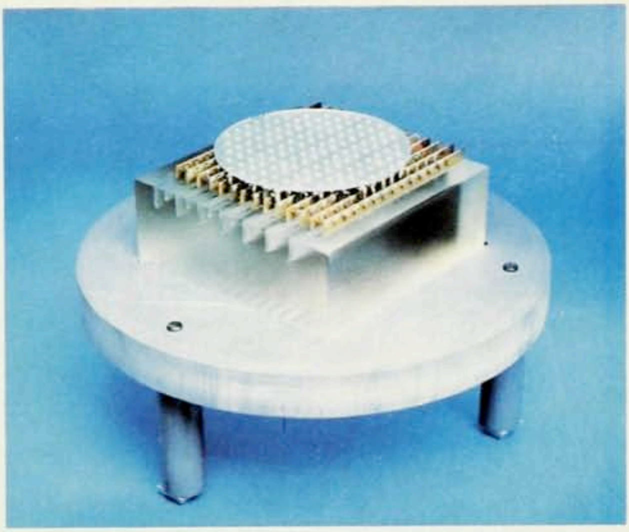
Observation of PBVs [post-boost vehicles] and RVs [reentry vehicles] (at 300 K) will require detection of weak thermal signatures since these signatures vary as T^4. Similar signatures are associated with objects in midcourse. Thermal detectors in the long wavelength infrared (LWIR) can be used only above the earth's limb against a cold sky background. Low noise LWIR detector assemblies having the appropriate resolution, i.e., large element arrays, are being developed. Because of the long wavelengths involved (8–12 μm), submicroradian tracking accuracy is not feasible in LWIR without using telescopes with apertures in excess of ten meters (Section 7.2). Thus, thermal detectors will have to be supplemented by some active means such as microwave or optical radars. A large number of space-based platforms will be required. These might be the same platforms that are performing similar duties in the boost phase (Section 7.3).

18. For midcourse, when the RVs are interspersed with penetration aids, interactive discrimination may be required. At present the application of DEW technologies to this task is in the conceptual and early experimental stage.

Missiles which survive the boost phase can deploy large numbers of decoys and other penetration aids. Since LWIR and radar signatures depend largely on surface phenomena, there are many options available to the offense desiring to confuse or saturate the defense (use of balloons for example). Directed energy technologies may offer the possibility of "mass" discrimination by interactive, perturbing means, e.g., detection of particle-beam-induced secondary emissions or velocity changes caused by laser-ablation-induced impulse. DEW platforms absent from the boost phase intercept theater might be useful in this function. Such interaction discrimination is in a conceptual and early experimental stage, and would require large numbers of additional sensor/detector platforms, plus the ability to function in nuclear-disturbed backgrounds (Section 7.7).

19. The development of an effective boost phase defense is highly desirable, perhaps essential for limiting the number of objects with which the midcourse and terminal defense elements must cope.

Given the present number of Soviet boosters and their capability, the offense can deploy half a million or more threat objects (reentry vehicles and decoys). Boost phase attrition is required if midcourse discrimination systems can deal with only a limited number of threat objects. Even an 80% effective boost phase defense would leave 100,000 or more objects entering the midcourse phase. If further in-



Adaptive optics, or "rubber mirror," component. To propagate efficiently through the turbulence of the atmosphere, laser beams must have their phase fronts adjusted. Adaptive optics achieves this compensation by moving the mirror segments individually to produce a phase front that exactly adapts to the turbulence-induced phase changes.

creases in the offensive threat or degraded performance of the boost phase tier overloads the tracking and discrimination capabilities of later tiers, then the overall performance of the defensive system would degrade catastrophically rather than linearly when saturation is approached. The tracking and discrimination of tens to hundreds of thousands of objects during the midcourse phase poses formidable challenges to sensors and battle management computers. If discrimination requires birth-to-death tracking of all threat objects, these problems become even more demanding (Section 2.3).

20. **Housekeeping power requirements for operational maintenance of many space platforms for strategic defense applications necessitate nuclear reactor driven power plants on each of these platforms.**

The power requirements for "housekeeping," i.e., the requirements for a space platform to control attitude, to cool mirrors, to receive and transmit information, to operate radars, etc. are estimated to be in the range of 100–700 kW of continous power. This would require a nuclear reactor driven power plant for each platform, necessitating perhaps a hundred or more of these nuclear reactors in space. These foregoing needs require solving many challenging engineering problems not yet explored. Cooling of large space-based power plants is a very difficult task (Chapter 8).

21. **During engagements prime power requirements for electrically driven space-based DEW present significant technical obstacles.**

The prime power required for electrically driven DEW, e.g., particle beam accelerators, is estimated to be 1 GW. This power could be provided by large chemical or nuclear rocket engines and generators, deployed at considerable distances or otherwise decoupled from the DEW platforms in order to avoid mechanical disturbances and effects of exhaust gases. This may require complex power transfer systems comprising cables, microwave systems, etc. Correspondingly, chemical fuel consumption would be more than five tons per minute of operation per platform (Section 8.3).

22. **Survivability is an essential feature of any BMD system employing space-based assets; such survivability is highly questionable at present. Evaluation of these issues requires a systems approach that includes hardening, active defense, and operational tactics. During the deployment phase, the space-based assets are especially vulnerable.**

The space platforms carry sensors, optical mirrors, or radar dishes, many of which have considerably lower damage thresholds than do the hardened boosters, post-boost buses, and RVs. While sensors and optical mirrors on satellite platforms may be shielded during long periods of inactivity, they would be exposed when put on alert prior to an impending ICBM attack. Such an attack could be preceded by an attack on these platforms by space-based and ground-based DEW, space-based kinetic energy weapons (KEW), space mines, or direct ascent nuclear and non-nuclear anti-satellite (ASAT) weapons of the offense. Moreover, the system must be developed by a process of accumulation of space assets while the system is less capable of defending itself (Sections 9.3 and 9.4).

The ground-based laser systems for strategic defense applications require a substantial number of space-based optical elements and space-based sensors. The space-based optical elements include telescopes with large primary mirrors, the size and numbers of which will depend on the basing modes for the relay and the fighting mirrors. These space-based elements entail the same vulnerability as any other space-based components (Section 9.3).

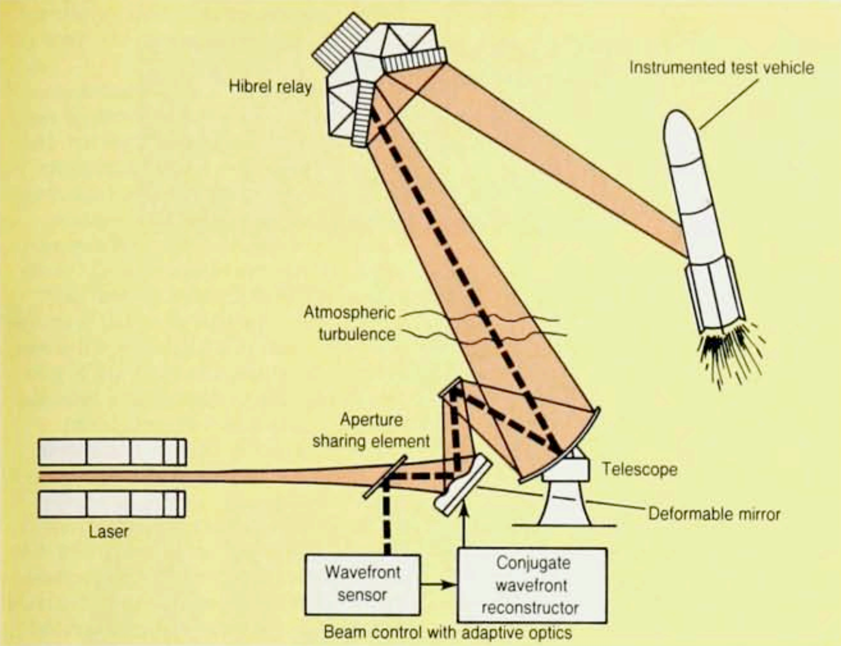
23. **Survivability of ground-based facilities also raises serious issues. The relatively small number of large facilities associated with ground-based laser sites makes these facilities high value targets.**

The ground-based laser BMD facilities must be successfully protected from direct attack from many threats (e.g., cruise missiles, sabotage, etc.), in addition to ballistic missiles. Thus, any strategic defense system depending on ground-based lasers, or on other ground-based facilities which cannot be extensively proliferated, must be effective in defending against more threats than just ballistic missiles (Section 9.3).

24. **Directed energy weapons with capabilities below those needed for many ballistic missile defense applications can threaten space-based assets of a defensive system.**

If a DEW falls short of ballistic missile defense requirements, it may still be a credible threat to space-based assets. Space-based platforms move in known orbits and can therefore be targeted over much longer time spans than ballistic missile boosters, post-boost buses or reentry vehicles. The defense platforms may have key components that are more vulnerable than the boosters and the reentry vehicles. Furthermore, space-based platforms in low earth orbits can be attacked from shorter ranges than those required for boost phase intercepts (Sections 9.3 and 9.6).

25. **X-ray lasers driven by nuclear**



Schematic drawing showing how adaptive optics (pictured in figure on facing page) could be integrated into a ground-based laser system. A downlink signal from the relay mirror, passing through the turbulence, tells the wavefront sensor how to cancel the atmospheric effects. A computer reconstructs the wavefront that will perform the compensation and drives the actuators that deform the rubber mirror segments by the precise amounts required.

explosions would constitute a special threat to space-based sensors, electronics, and optics.

The high energy-to-weight ratio of nuclear explosive devices driving the directed energy beam weapons permits their use as "pop-up" devices. For this reason the X-ray laser, if successfully developed, would constitute a particularly serious threat against space-based assets of a BMD (Sections 3.5 and 9.3).

26. Since a long time will be required to develop and deploy an effective ballistic missile defense, it follows that a considerable time will be available for responses by the offense. Any defense will have to be designed to handle a variety of responses since a specific threat cannot be predicted accurately in advance of deployment.

A thorough understanding of practical responses, such as attacks on the defensive assets, hardening of offensive systems, and rapid deployment of large number of decoys, must be established before conclusions about the technical feasibility and cost-effectiveness of a defensive system can be made. A DEW system designed for today's threats is likely to be inadequate for the threat that it will face when deployed (Section 2.3 and Chapter 9).

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Postscript: Reviewers and authors comment on report

The review committee for the DEW study, headed by George Pake, transmitted the report to the APS Council on 20 April. In his transmittal letter, Pake noted that recent statements from the Strategic Defense Initiative Organization indicated that kinetic-energy weapons, not directed-energy weapons, are being emphasized as a short-term strategy for ballistic missile defense. Under such plans DEWs are largely relegated to discriminating against decoys, he wrote. Although the study dealt with both decoy discrimination and target destruction, it emphasized the latter. The study group had not been charged with examining kinetic-energy weapons components or systems; while the study was under way, SDIO shifted its emphasis.

Pake wrote that three related topics relevant to the APS study group's charge are not treated in the report:

▶ "No evaluation was made of how well the R&D program is being carried out, given its objectives. In view of the classified nature of the program and the broad range of activities undertaken, such an evaluation could not realistically have been made by the study group."

▶ "The cost of a program necessary to achieve any given level of defense capability was not estimated. Not enough is known at present about the hardware to be deployed to make such a cost estimate with any accuracy. In addition, costs would depend on the pace of the program—whether, for instance, several potential solutions to a problem are pursued in parallel—on