

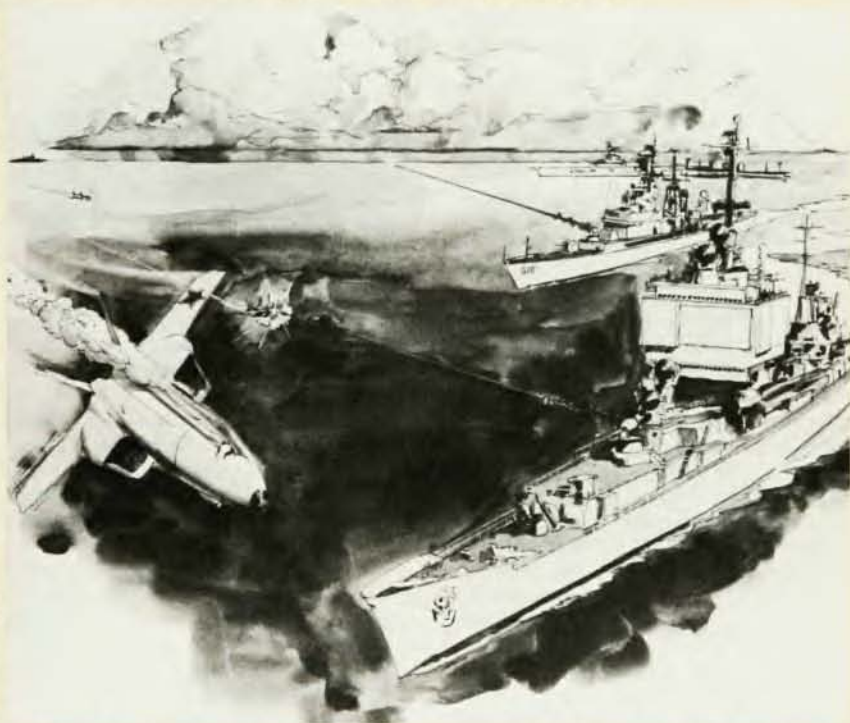
Directed energy weapons—where are they headed?

A futuristic look at the nation's defensive weapons systems sometimes includes visions of space-based lasers or particle beams, able to direct their energy precisely and devastatingly upon any target. The Defense Department has several technology programs that deal with these directed-energy weapons, although practical implementation appears to be at least a decade away. President Reagan may now wish to place more stress on such programs. In a speech to the nation on 23 March, the President proposed a "comprehensive and intensive effort to define the long-term R&D program" on defensive weapons against ballistic missiles. He hoped to ensure peace by rendering such nuclear weapons launchers "impotent and inoperative." One ingredient of such a program might be a land- or space-based system of lasers and particle beams.

Responding to the President's initiative, officials within the White House and within the Departments that sponsor directed-energy research have begun to evaluate the various technology programs. They intend to identify the most promising ones, to decide the appropriate level of emphasis for each and to develop a program plan that might be incorporated into the budget proposal for fiscal year 1985. Their review is being conducted away from the public eye.

The President's speech has also rekindled the controversy over a defense based on directed-energy systems and has sparked curiosity about the status of work on such weapons. What missions might such weapons systems fulfill? What hurdles currently block the way to practical realization of these systems? What arguments are being made for and against directed-energy weapons systems as the cornerstone of the US defense against nuclear attack? We set out to survey the programs in progress and to listen to the ongoing debate.

Possible defensive missions. The role most often envisioned for directed-energy weapons is to defend the US against enemy nuclear missiles. Both lasers and particle beams show promise



Defense of ships is one possible role for charged-particle beam weapons. Because of problems with beam stability, they may have ranges of only a few kilometers in the atmosphere.

for such a role because the beams arrive at their target at or nearly at the speed of light and because they deliver a destructive quantity of energy in a very short time. The first characteristic means that the weapons can be aimed along the line of sight (although at long ranges, the beam must lead the target by a slight amount). Evasive actions by the target are not possible. The second enables the weapon to engage many targets very quickly, provided, of course, that the power supply is adequate for numerous refires. Laser beams can be directed at targets attacking from any direction, but particle beams are restricted to a narrower angular range.

A typical weapons system (as discussed in the laser- and particle-beam fact sheets published by the Department of Defense),^{1,2} whether based on land or ship, in air or space, consists of the beam source, a beam-control sub-

system to direct the beam and to keep it pointed on its target, and a fire-control subsystem to identify each target, discriminate it from decoys, determine whether a given shot was successful and to redirect the beam accordingly. To exploit fully the unique advantages of a directed-energy weapon, these subsystems have stringent requirements placed upon them. First, the targeting must be precise because these weapons can damage an object only by making direct contact with them. The distances over which these shots are fired in space make this targeting task especially difficult. The control systems must keep the beam focused on one spot of the target long enough to do the requisite damage. Furthermore, the fire-control system must be very fast, especially if one envisions defense against a massive attack.

The two types of missions might be classified roughly according to whether

the weapon is based within the atmosphere or outside it. Endoatmospheric missions can include the point defense of a large ship such as an aircraft carrier, the hard-site defense of intercontinental ballistic missiles, or airborne strikes with laser beams against satellites. The range required in the first two applications is typically only a few kilometers. Exoatmospheric missions could involve defense against ballistic missiles or enemy satellites. For such space missions a number of directed-energy weapons stations is required so that at least one remains in sight of every potential ballistic missile trajectory. The higher the orbit, the fewer the stations needed but the longer the strike range. Some estimates of the number of stations required were made as part of a study undertaken by physicists at MIT several years ago.³ For a synchronous orbit, at an altitude of about 40 000 km, only a handful would be required. For a low Earth orbit, the range might be reduced to about 1000 km but the number of weapons stations might be increased to around 150 to 200.

Another type of mission might involve a combination of endo- and exoatmospheric basing. According to testimony⁴ given by Edward Teller before a subcommittee of the Senate Armed Services Committee, defense planners have proposed "pop-up" defense systems that are sited on Earth but launched into space in times of crisis. Such systems would be less vulnerable than permanently orbiting space stations but, as some critics say, might not necessarily be launched in sufficient time to engage an enemy target.

Laser systems encounter several sources of degradation when shot near the Earth. Some of these were examined in a study of laser weapons done⁵ at MIT in 1980. Molecules and particulates within the atmosphere absorb and scatter the radiation, limiting the weapon's range in clear weather and virtually neutralizing it on foggy or rainy days. Even in good weather, the beam would diverge through an effect known as "thermal blooming." In this effect, the beam spreads out at the edges because the heated air in the beam channel has a lower index of refraction. Turbulence in the air further bends and defocuses the laser beam. Although current studies are exploring the problems of beam propagation in the atmosphere, the existence of such problems makes the space-based applications of lasers more attractive. For space applications, the challenge is to design an efficient and powerful laser and an optically precise, suitably large pointing mirror.

The missions envisioned for particle beams vary with the type of particle. Charged-particle beams cannot remain

focused over the distances required in space because the mutual repulsion of the charged particles is greater than the focusing effect of the magnetic fields generated by the beam. Charged-particle beams are further limited in space because of the deflection by Earth's magnetic field and because of the space charge that the accelerator develops outside the atmosphere.³ Thus weapons systems based on streams of particles such as electrons can only be used within the atmosphere and over very short ranges. In the atmosphere, the beam becomes electrically neutralized by ionization of the ambient atmosphere; thus the magnetic field generated by the beam helps to focus it. One might be able to ameliorate the atmospheric attenuation of the beam by pulsing it: Each successive pulse might further evacuate a channel in which the next pulse could travel. Still, problems such as beam stability have created considerable doubt about whether particle-beam weapons can ever be used for ranges beyond a few kilometers in the atmosphere. The study of beam propagation in the atmosphere is one of the major items on the agenda of the particle-beams program.

Neutral beams might be used for weapons systems based in space. They would not be susceptible to the spreading caused by repulsive forces nor to the bending by the Earth's magnetic field. The major technical problems are to produce a neutral beam of low initial divergence and high current density, and to design a fire-control system that accounts for the inability to determine the error in directing the beam.³

The challenges posed by these various missions are being addressed in the technology programs sponsored by the Defense Advanced Research Projects Agency, the Air Force, the Army and the Navy. These organizations are exploring numerous laser concepts and have built several particle-beam accelerators as well as systems for beam and fire control. This spectrum of programs is closely coordinated by the Assistant for Directed Energy Weapons in the Office of the Under Secretary of Defense for Research and Engineering. The level of funding in FY 1983 is \$375 million for the high-energy laser program and \$47 million for the particle-beams program. The Department of Defense request for FY 1984 is \$469 million and \$50 million for the two programs, respectively.^{1,2}

The high-energy laser program. DARPA has undertaken a three-pronged approach to study the practicality of a laser weapons system in space. The first component of its program, Alpha, is aimed at the fabrication and testing of a high-powered chemical laser. The second component, the large optics

demonstration experiment, is directed at the problem of constructing the high-quality mirror. The third component, Talon Gold, is a planned spaceborne pointing and tracking experiment. The Air Force has an Airborne Laser Laboratory, which consists of a carbon dioxide laser mounted into a NKC-135 cargo aircraft. The Air Force has used this Laboratory to engage air-to-air missiles in flight. The Navy has also been conducting tests of laser systems, using chemical hydrogen or deuterium fluoride lasers. In a series of tests at San Juan Capistrano in 1978, a laser of this type together with a pointer-tracker successfully intercepted and destroyed some TOW antitank missiles. The Navy is planning another series of tests, called Sea Lite, in the mid 1980s at the High Energy Laser National Test Range now being developed at the White Sands Missile Range in New Mexico. From such programs, the Air Force and Navy should learn more about the damage to targets from lasers as well as about the behavior of specific system designs. The Army is interested in a laser as a possible weapon in the forward-area battlefield.

The key ingredient in all these programs is, of course, the laser. We spoke about some of the laser research with Douglas Tanimoto (Maxwell Labs), who was formerly head of the directed-energy weapons program at DARPA. In addition to developing high-power chemical lasers (the quantitative power goal is classified), the advanced research is directed to short wavelengths, to limit the restrictions imposed by diffraction spreading of the beam. In space, a laser beam reflected from a mirror has an angle of divergence that varies directly with the ratio of its wavelength to the diameter of the mirror. To keep the size of the mirror as small as possible, the laser wavelength should be as short as possible. Another advantage of the shorter wavelengths is that the radiation couples better to metal targets. The other side of the coin is that the specifications on the optical quality of the reflecting surface become more stringent for shorter wavelengths.

The first high-power laser was the carbon-dioxide laser, which radiates at 10.6 microns. In this gas-dynamic laser, the population inversion results from the rapid expansion of a gas. In a chemical laser, the molecules are formed in the excited state and held there long enough for the lasing to occur. One common type of chemical laser is the hydrogen fluoride laser, which operates at a wavelength around 2.7 microns. Using deuterium instead of hydrogen changes the wavelength to about 3.8 microns, making it less susceptible to atmospheric absorption.



Sandia's radial line accelerator (RADLAC) and Livermore's Advanced Test Accelerator are exploring charged-particle beam technology. In this photo of RADLAC, a generator charges an intermediate storage capacitor (left) to energize the injector. Accelerating voltage is applied synchronously by radial pulse lines (right rear). The accelerating gradient is 5 MeV/meter.

The Navy and the Army appear interested in both HF and DF lasers. A general review⁶ of laser and particle-beam weapons in *Aviation Week and Space Technology* pointed out that because the toxic gases pose a potential health hazard for the Army's land-based missions, the Army has developed a chemical pump to operate the laser in a closed cycle. Another type of laser is the electric-discharge laser in which an electron beam imparts its energy to excite the gas molecules to vibrational states.

Two more advanced concepts are also being studied within the directed-energy weapons program. They are the excited dimer (excimer) laser and the free-electron laser. In the excimer laser, electrons bombard a noble gas such as xenon or krypton and strip the outer electrons. The resulting ions, in their excited state, react chemically to form such compounds as xenon fluoride or krypton fluoride, which constitute the inverted population for lasing. The wavelength of excimer lasers is in the submicron region.

The free-electron laser is more like a traveling-wave tube than a laser. It consists of a beam of relativistic electrons sent into a wiggler magnet, which produces a static transverse magnetic field whose value varies with distance in a periodic fashion. The motion of the electron in the periodic field produces electromagnetic radiation whose wavelength equals that of the wiggler divided by a factor proportional to the square of the kinetic energy of the

electrons. Therefore, if one uses high-voltage accelerators to produce the beam, not only can the wavelength be short but it can be tunable. When there is an initial field of the appropriate frequency, the free-electron laser acts as an amplifier.

We spoke with Charlie Brau (Los Alamos National Lab) about the experiments with free-electron lasers there. About a year ago they operated such a device and claim to have demonstrated an efficiency of 3.5% for conversion of energy from the electron beam to the laser radiation. With an energy-recovery scheme they have devised, they hope to reach an efficiency of 20%. Many other labs are also working on free-electron lasers.

The newest laser on the horizon is the x-ray laser. Lawrence Livermore Laboratory may have tested an x-ray laser that was pumped by a small nuclear explosion (*PHYSICS TODAY*, June, page 61). Apparently the idea is to have one such explosion power numerous x-ray lasers in space, all pointed at different targets.

Particle-beam weapons. Particle beams can transfer a larger fraction of their energy to the target in a given amount of time than laser beams, which are subject to reflections and other interactions with the surface. Particle beams deposit their damaging energy further beneath the surface than do lasers and would thus be more effective for damaging internal components but less efficient for heating the outer surface of a target. The techno-

logy for particle-beam weapons lags behind that of laser beams by a considerable extent. While the US has extensive experience in accelerator design, the requirements for a military application are considerably different.² The particle-beam weapon facility must deliver a high current at a rapid pulse rate.

One of the major components of the program in charged-particle beams is the Advanced Test Accelerator, completed in Fall 1982 at Livermore (*PHYSICS TODAY*, February 1982, page 20). This machine is an induction linear accelerator that is designed to produce 50-MeV electrons at a current of 10 kiloamps. Its main purpose is to test the propagation of a pulsed charged-particle beam in the atmosphere. A second charged-particle accelerator, called RADLAC, is being operated by the Air Force Weapons Laboratory and Sandia National Laboratory; it uses pulsed power-transmission lines to apply voltages to the linear accelerating gaps. This design lends itself to very high accelerating gradients—between 3 and 5 MeV per meter—but cannot be pulsed rapidly. Like ATA, it is being used for studies of atmospheric propagation.

The neutral-beam program, called the White Horse program, is centered at Los Alamos. Neutral beams of hydrogen are produced by accelerating negatively charged hydrogen ions and stripping them of their charge at the end. The heart of the Los Alamos program at this time is a radiofrequency quadrupole preaccelerator that forms micropulses at 420 Hz acceptable for input into a drift-tube linac (not yet on line). Harald Dogliani, program director of White Horse, described the design of the rf quadrupole to us by comparing the vanes of the quadrupole to bread knives: Each "blade" is longitudinally parallel to the accelerator axis and set at right angles to the others; the serrated edges point into the axis and modulate the electric field, which accelerates and focuses the beam. The modulator produces both beam bunching and acceleration in a relatively compact space. The quadrupole is 2.9 m long and can accelerate a beam up to 2 MeV. The Los Alamos team based their designs for both the ion source and the rf quadrupole on concepts that were first described in the open Russian literature. Pierre Grand (Brookhaven) told us that V. V. Vladimirovskij and I. M. Kapchinskij (Institute for Theoretical and Experimental Physics, Moscow) hold a Soviet patent for the rf quadrupole.

Dogliani said the purpose of the program is to determine the military feasibility of particle-beam accelerators; the potential applications are for ballistic-missile defense or for antisa-

tellite weapons. The White Horse group is striving to obtain a high-intensity beam with a low effective temperature. The effective temperature is a measure of the divergence of the beam.

Controversy over the weapons. Does the idea of "bullets" fired by laser or particle-beam "guns" make any sense? Critics have often made assessments of the weapons and their missions and have concluded that they are not practical. For example, Richard Garwin (IBM) has estimated that the ballistic-missile defense by lasers based in space would require an increase in laser brightness of at least a factor of 10^6 over what had been demonstrated in any ground-based system.⁷ For an antisatellite beam weapon in synchronous orbit he calculated that the energy required would be some 80 tons of fuel (with concomitant transportation demand of at least 8000 tons of rocket fuel). In response, defenders of the directed-energy weapons program state that such calculations of the numerical requirements of the mission are too often based on numbers that err by orders of magnitude on the conservative side. Tanimoto noted that, for instance, estimates of the required laser brightness have ignored the great strides that have been made in pointing stabilities. He mentioned that the Soviet Union has a considerable effort in directed-energy weapons technology; he feels that the US also needs to move ahead with the technology to under-

stand better its limits and capabilities.

Beyond the question of whether an individual directed-energy weapon can now or in the future destroy its assigned target lies the larger question of whether an entire defense system based on such weapons can be effective against the full range of attacking missiles. To many critics, these capabilities are separated by a large gap. Wolfgang Panofsky (SLAC) commented to us that a defense system costs too much if the other side can defeat it for less (and it might simply fuel the arms race in the process). The offense has available a wide variety of relatively inexpensive countermeasures to any directed-energy defense. For example, the offense might coat all satellites or launchers with highly reflective material to minimize absorption of laser energy, use decoys to confuse the fire-control systems, or jam the communications links to the space-based weapons. The ultimate countermeasure would be the destruction of the space-based weapon itself with space mines. Panofsky said that in the past the cost of defending a country against nuclear attack has always been much larger than the price of countermeasures to nullify that defense; he knows of no studies indicating that a directed-energy defense would be any different.

A final concern of critics of the directed-energy weapons is that they may represent the introduction of weapons into space. Garwin has pointed out the valuable and stabilizing roles

served by our present communications and surveillance satellites. He and others would not like to see those satellites threatened by introduction of destructive machines into space. Garwin and Carl Sagan (Cornell) prepared a "Petition For a Ban on Space Weaponry," which was signed by more than 40 scientists and strategists. They presented the petition to Congress in May. At the same time, Garwin, together with Kurt Gottfried (Cornell), presented a draft treaty prepared under the auspices of the Union of Concerned Scientists that calls for a ban on the testing and use of weapons in space.

—BGL

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Less-elusive neutrinos to look for oil and gas deposits

Four well-known particle physicists recently went public with a far-out scheme using high-energy neutrinos to explore far into the depths of the Earth. The group—Alvaro De Rújula (CERN), Sheldon Glashow (Harvard), Robert R. Wilson (Columbia) and Georges Charpak (CERN)—suggested a number of such geological studies: exploration for oil, natural gas and high-Z ores, and determination of the vertical density profile of the Earth.

A few years ago particle theorist De Rújula revived the notion of using a high-energy neutrino beam for exploring the Earth geologically. He then convinced fellow theorist Glashow, accelerator-builder Wilson, and detector-designer Charpak to join him in studying the ramifications of such an approach. Two years later the team has produced a Harvard preprint, HUTP-83/A019 (dated March 1983), "Neutrino Exploration of the Earth," 113 pages long, which is to be published in *Physics Reports*. Written in a lively, provocative fashion, the preprint considers some of the technical and scienti-

fic questions associated with using a neutrino beam as a remote sensor.

They write, "Perhaps, neutrinos will be for geology what x rays were for medicine. What is needed for 'whole-Earth tomography' is a form of radiation whose range in matter is neither very much greater nor very much smaller than the size of the Earth. . . . Neutrinos with energy of few TeV are just right, having a range only somewhat larger than the Earth's diameter."

The Geotron accelerator. The source of these TeV-range neutrinos would be the Geotron, an underwater proton synchrotron, say 6–12 km in radius, that would produce 10- or 20-TeV protons. The extracted proton beam would hit a target and produce an intense, highly collimated beam of pions and kaons. These would pass through a long decay tunnel where the mesons would turn into a neutrino beam. This elaborate system of proton beam transport, target and decay tunnel, called the Snout, must be siveled with great precision and aimed at remote sites. Both the Snout and Geo-

tron might be floated at sea to increase their maneuverability. About ten years ago, Wilson had jokingly described an enormous floating accelerator docked at Tahiti.

If the design of the Tevatron, expected to produce 1000-GeV protons early next year at Fermilab, were extrapolated to 10 TeV with similar magnets, the team estimates the Geotron would cost \$2 billion. With better design and improved magnets (using niobium-tin and reaching 7.5 tesla instead of the Tevatron's niobium-titanium that reaches 5 tesla), the group argues the Geotron might cost about \$1 billion. "By more ingenious people, it might cost less; but it might cost very much more if built under the loving supervision of present-day bureaucrats. The construction could well be drawn out in a jobs-for-all Nirvana, for years as the costs double and then double again. This sobering pitfall for projects is not, experience informs us, the exception." But the group is optimistic and estimates construction would take three years after funding at \$1 billion. To