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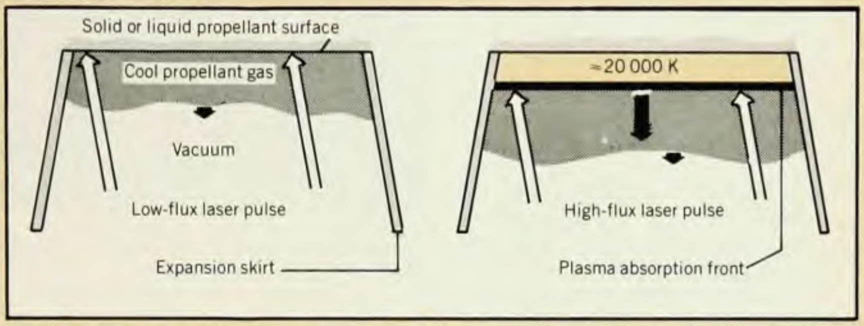
Space vehicles could be propelled by remote lasers

Interest is apparently growing in using a high-energy laser to power a vehicle that is a considerable distance away from the laser. The laser can be located on the ground and used to propel a spacecraft into orbit or even to power an airplane. Alternatively the laser can be located in orbit itself and used to propel a spacecraft into higher orbit.

The laser can cause rapid evaporation, producing a supersonic jet, or at higher fluxes the vapor can be ionized, producing a very high specific impulse—about a thousand seconds.

Both the Defense Advanced Research Projects Agency and NASA are supporting small research programs in laser propulsion. Among the laboratories known to be working in the field are Avco-Everett Research Laboratory in Everett, Mass., Physical Sciences Inc. in Woburn, Mass., Rocketdyne Division of Rockwell International in Canoga Park, Calif., NASA Lewis Research Center in Cleveland, Ohio and the Lebedev Physics Institute in Moscow.



Laser-sustained detonation-wave rocket engine. In step 1 (left), a low-flux laser pulse ablates a measured amount of propellant gas from a solid propellant surface or from a liquid film on a porous plate. In step 2 (right), a high-flux pulse ignites a laser-sustained detonation wave at the surface. A front of highly absorbing plasma, which shields the surface from further laser radiation, propagates back towards the laser, heating the gas propellant to roughly 20 000 K. The beam is turned off when the front has passed through most of the gas. The cycle is repeated after the hot gases have expanded. Figure from Avco-Everett Research Laboratory.

Agencies. DARPA is spending about $500 000 next fiscal year, divided between Avco and Physical Sciences, with the emphasis on earth launching of military payloads into space. An ARPA official said that such a system would use very large lasers to launch small payloads at a cost of 10^9 watts/ton of payload to orbit. However, he would not discuss existing laser capability, although he did say carbon-dioxide electric-discharge lasers were being considered. DARPA director George H. Heilmeier, in a report to Congress this year, said that the Defense Department has been constrained by the

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Sandia and Kurchatov groups claim electron-beam fusion

Experimenters at Sandia Laboratories in Albuquerque, N.M. believe they have produced about a million neutrons per pulse from thermonuclear fusion induced by bombarding a pellet with an electron beam. Last year Leonid I. Rudakov and his collaborators at the Kurchatov Institute in Moscow had reported the production of similar amounts of fusion neutrons produced by electron beams. However, Gerold Yonas, who heads the Sandia Fusion Research Department, believes that his group is the first to use the so-called "magnetic thermal insulation" principle, which allows relatively low power to be used in the electron beams. The electron-beam yields are about a factor of 1000 less than that achieved thus far with lasers.

The Sandia experiment and theoretical analysis, done by James T. Chang, Archie V. Farnsworth, Ramon J. Leeper, Thomas S. Prevender and Melvin M. Widner, uses an electron-beam accelerator called Rehyd, which is of the Hydra type; it employs a water-insulated pulse-forming line. The device, operated at 1 MV, produced 250 000 amps lasting 80 nanosec. The first experiment was carried out last fall, testing a concept that was proposed by the Sandia group in 1975.

The deuterium-fueled target was of the exploding pusher type and was 3 mm in diameter, about 30 times wider than typical laser-fusion targets. The single electron beam was sufficiently wide that it bathed the entire target. One gets symmetrical bombardment because the beam behaves as a fluid, with a large component of random velocity, Yonas explained. The maximum beam power was 25×10^{10} W, and the Sandia group believes the actual power absorbed is about 4×10^{10} W. This attenuation occurs because the Rehyd diode was not ideally suited to efficient focussing. In addition, to get symmetric irradiation with a single beam, the target has to be smaller than the beam and furthermore, because the target is thin, not all the energy is absorbed.

Although simple calculations would indicate relatively high power requirements for initial neutron experiments, Yonas says that Sandia has obtained fusion neutrons at a relatively low power level because of symmetric irradiation,[1] enhanced coupling in the thin shell due to beam stagnation,[2] and the use of the magnetic thermal insulation principle.

To reach thermonuclear temperatures at the low power level available on Rehyd, just an imploding shell will not work, Yonas explained. Instead, in magnetic thermal insulation, a portion of the beam is allowed to penetrate the target. This produces initial heating of the fuel, and also a magnetic field that thermally isolates the plasma from the imploding shell. Theorist John Nuckolls (Lawrence Livermore Laboratory) explains that one has a B_θ field, so that the field lines are closed loops; thus end effects disappear. However, a very complicated geometry is required. The field configuration resembles an imploded toroidal plasma, he said. For the magnetic field to get large enough to inhibit thermal conduction, it has to be the advantages of longer pulse length, because of questions of hydrodynamic instabilities in very large aspect-ratio targets. (The aspect ratio is the ratio of the target radius to the thickness of the shell.) The Lebedev theorists believe aspect ratios as high as 100:1 could be useful, whereas the Livermore theorists feel that thicker shells are more likely to be successful. Yonas notes that experiments to test whether or not either theory is correct have yet to be carried out.

—GBL

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cost ($1000/pound) of putting payloads into orbit. The DOD space-shuttle effort hopes to cut this cost to $400/pound with reusable vehicles, but for many applications DOD would like to put large numbers of moderately sized systems into widely dispersed orbits, he said. For this application, laser propulsion is being considered. Heilmeier envisions focussing laser energy into a rocket engine, where a hydrogen plasma is heated to 3000–4000 K, producing a specific impulse of 1000 seconds, three times that available with conventional chemical fuels. Because the laser system remains on the ground, this "permits rapid cycling, extremely high capacity and amortization of the system over very many launches, driving the cost per pound to orbit down dramatically." The DARPA official believes "laser propulsion holds the promise of being able to insert payloads into high orbit for as little as $30–$50/pound."

Several difficulties with laser propulsion were identified by the DARPA official: ability to produce and contain the laser plasma required for specific impulse of 1000 seconds, economics of fabricating and recycling laser, optics and engine, development of very high-powered lasers, and ability to deliver high-energy laser beam to engine.

NASA is spending about $100 000–$150 000 per year on laser propulsion, and on high-power laser technology applications in general is spending $1–1.5 million per year. NASA is emphasizing lasers for power in space, orbital maneuvers and deep-space propulsion, not earth launching.

Avco-Everett's chairman, Arthur Kantrowitz, is enthusiastic about using lasers to propel vehicles into geosynchronous orbit. For such an application to be feasible, one must assume that a laser with 1 GW average power is possible, or that several smaller lasers with the same total can be assembled. Kantrowitz notes that Avco announced in 1971 a 135-kW gas-dynamic laser that can run for a long time, provided gas is continuously supplied. He says he cannot argue about the reasonableness of higher power lasers, "But maybe we could do better." With the growth of adaptive optics, one can produce mirrors that are flexed with quartz crystals or magnetostrictive elements so as to produce a figure on command to respond to atmospheric aberrations, which can be produced by the laser beam itself. One assumes the optical system can focus with an accuracy of 1 microradian, so that at 1000 km one can focus to 1 meter.

Another assumption is that a gigawatt beam will go through the atmosphere. If a carbon-dioxide laser is used, atmospheric absorption would be serious, Kantrowitz said, because of water vapor in the atmosphere. However, if the laser is placed on a mountaintop, say at 10 000 feet, the chief absorption source is carbon dioxide in the atmosphere. And that absorption can be bleached with a carbon-dioxide laser so that all the carbon-dioxide molecules are put in the upper state; then the atmosphere becomes transparent. From Avco's point of view, propagation appears feasible.

For sea-level-based lasers, thermal blooming can be a problem, according to Jan Herrmann (Lincoln Laboratory). Thermal blooming occurs because absorption of the laser energy heats the air, lowering the density and consequently the index of refraction, so that the beam spreads. The problem is especially severe for cw lasers, Herrmann notes. With the rapidly pulsed, wide-diameter laser beams being considered, thermal blooming from the pulses is comparable to that of cw radiation, he said. However, adaptive optics would be helpful. To correct for thermal blooming, a response of 10 Hz is sufficient. But to correct for atmospheric turbulence, he said, higher frequencies are needed, although at the 10 000-foot altitude being considered by Avco, turbulence and thermal blooming are less important.

As a receiver for the laser radiation, Kantrowitz envisions heating a propellant to about 10 000 K. The propellant might be a reinforced cake of ice. Two pulses would strike the solid propellant. The first, lasting tens of microseconds, would have a flux of 10^6 W/cm^2 and would evaporate the propellant. The second pulse, lasting about half as long and with powers of several times 10^7 W/cm^2, would strike the base of the rocket, impinge on the predisposed gas and ignite a laser-driven detonation wave. The process would heat the gas to 10 000–20 000 K, and the expanding gas would provide thrust. Around the base of the rocket would be a skirt, 0.5–1.0 meters long, which would confine the propellant during expansion.

The transmitter mirror would be kept focussed on the propellant, while receivers on the vehicle would transmit information needed to correct the mirror's figure. Kantrowitz explains that one would propel the vehicle to about 1000 km, it would coast up to orbit and then one would "deliver a kick in the apogee" to circularize the orbit.

Dennis Reilly of Avco told us that the exhaust velocity should be roughly equal to the mission velocity, 8–11 km/sec, and the specific impulse should be 800–1000 seconds. In Avco's model, they find that efficiencies of about 50% should be possible. A large-scale laser would deliver 10 MJ/pulse at a rate of 100 pulses/sec or 1 MJ at 1000 pulses/sec.

In Avco experiments, they used 300 J/pulse, depositing energy into a small (1.5 × 30 cm) cylindrical chamber at atmospheric pressure. They monitored expansion at the nozzle and found the pressure–time profiles agreed with calculations. Now they plan to run larger-scale, higher-energy experiments in vacuum.

Kantrowitz proposes a system that would launch one ton into synchronous orbit every few minutes, putting 100 000 tons/year of freight into orbit. He feels it could be operated with ordinary commercial safety standards, reducing costs to $20/pound.

Another idea for laser propulsion has been patented by Kantrowitz and Richard Rosa. They would use a laser to propel an airplane, which would have a range of 50.miles. The propellant would be air. Kantrowitz believes one good application of the idea would be to fly an airplane at 100 000 feet to serve as a television antenna. Such a scheme would have a line of sight ten times better than an antenna atop the Empire State Building.

Physical Sciences. The major program at Physical Sciences Inc. is also built around a pulsed laser and is supported by DARPA. Microsecond pulses strike a reflector that can focus the energy, causing the gas to be electrically broken down. The sudden heating produces a blast wave, similar to the chemical detonation scheme studied by NASA. The blast wave processes another batch of gas, heating and accelerating it. This gas passes through a rocket nozzle, which functions as a dual collector and nozzle. The gas is reintroduced through the nozzle throat at a rate determined by the nozzle, in a process known as "acoustic valving." A theoretical treatment of the entire process has been produced by Girard Simons (Physical Sciences).

Robert F. Weiss, president of Physical Sciences, told us that many low-density expellants are possible, such as water vapor, ammonia or hydrogen. In laboratory experiments, Anthony Pirri and Peter Nebolsine used helium, which was struck by radiation from four TEA carbon-dioxide lasers, producing 10 J each, fired sequentially at intervals of 10–100 microseconds. As the experimenters approach shorter times between pulses, they expect to run into an acoustic-valve limitation. Experiments so far were done at ambient pressure, and have generated a specific impulse of more than 900 seconds.

New experiments will be done in a vacuum chamber and are expected to improve the specific impulse 25%. In the future, Physical Sciences plans to experiment with various expellants, optimize the collector/nozzle, increase the energy and reduce the pulse repetition rate. They also plan to study the effect of varying the angle of incidence between the nozzle axis and the optical axis of the laser beam.

Weiss envisions the Physical Sciences system as useful for moving from low earth to high earth orbit or producing a ground-based high launch-rate system that could raise 2 tons at a time—"a conveyor belt to the sky." The laser would need 1 MJ/pulse, with 350 pulses/sec for a 2-ton payload and would generate 20 000 pounds of thrust.

NASA supports research at Physical Sciences using cw lasers for operation outside the atmosphere. In this work Physical Sciences has been studying absorption through a laser window. They have considered using hydrogen as an expellant, alone or with various seed materials, such as sodium or cesium. In another approach, discussed by Pirri and Weiss, one introduces air from a hypersonic inlet, and pulses the laser in the Physical Sciences system studied for DARPA.

In experiments being done by Lewis Research Center, a cw carbon-dioxide laser heats hydrogen plasma on the subsonic side of the nozzle, the gas flowing in the same direction as the laser. The absorption wave is supported by the laser. The objective is to heat hydrogen to 15 000–20 000 K.

The NASA program concentrates on orbit-to-orbit propulsion. A cw laser transmitter energized by the Sun might be located at 500-km orbital altitude. The laser would transmit energy to a rocket. Because the rocket is so far from Earth gravity, the thrust required to launch a 5000-pound payload would be only 50–100 pounds. In the NASA concept, a laser would strike a 1–2-meter mirror on the rocket. The beam would be focussed and used to heat hydrogen. The energy conversion could involve inverse bremsstrahlung or excitation of vibrational levels of molecules.

Besides supporting Physical Sciences, NASA has funded Rocketdyne Division of Rockwell International. They have built a tiny thruster whose throat is the size of a hypodermic needle. The thruster will be tested at Lewis Research Center. Lockheed is doing a systems study to see how laser propulsion from orbit to orbit compares to a conventional chemical system. So far, NASA's Carl Schwenk and Frank Stephenson feel that the laser approach looks reasonably promising.

The Lebedev Institute is considering[1] a solid-propellant (such as graphite) cw laser jet engine. If the propellant is heated to too high a temperature, a breakdown wave is produced. To avoid this, one must heat below the threshold, and according to Reilly, this limits the effective specific impulse to about 600 seconds. In addition, Lebedev is also considering a laser air-breathing jet engine similar to that of Kantrowitz and Rosa. —GBL

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Electron storage ring from Cornell synchrotron?

If Congress approves President Carter's science budget, Cornell University will proceed with plans to convert the Wilson Laboratory synchrotron facility into an electron storage ring. The President's budget includes an NSF request for funds to build the storage ring (known as CESR); design and prototype stages are already well advanced. The storage ring is to be housed in the synchrotron tunnel, and—in a novel injection scheme—the synchrotron itself injects electrons into the ring. Maximum design luminosity is $10^{32}/\mathrm{cm}^2\mathrm{sec}$ at about 8 GeV, so that the efficient operating range for CESR lies between that of existing storage rings (SPEAR at Stanford and DORIS at DESY) and the PETRA and PEP rings now under construction. Both SPEAR and DORIS have maximum beam energies of about 4 GeV, whereas PEP and PETRA are to have maximum luminosity at energies of about 15 GeV. In the range 4 GeV–8 GeV, the CESR design calls for four times the luminosity of the higher-energy rings. This is a particularly important consideration because, in storage rings, all experimental areas must operate at the same energy at any one time, and colliding-beam experiments can take several months, even at high luminosities.

To keep costs down, the plans call for developing only one of the two interaction regions as a major experimental area, at least at first. This area will be in the present South Experimental Hall. A group of some 40 physicists from the University of Rochester, Cornell, Harvard, Rutgers, Syracuse and Vanderbilt Universities are busily designing a general magnetic detector with maximum flexibility. "We're trying to use the previous experience of SPEAR and DORIS as a guide in designing the detector," commented Maury Tigner, director of operations at the Laboratory, in our conversations with him.

As Tigner explained to us, the magnet will be a solenoid—superconducting if possible—with a 2.0-meter inner diameter and a length of 3.2 meters. Within the coil, experimenters will be able to observe charged-particle trajectories and detect photons at small angles. Outside the coil, shower counters will measure photons, and a combination of time-of-flight, dE/dx and Cerenkov counters will identify particles. Surrounding all these detectors will be a thick shield of iron interleaved with muon detectors. The goal is to be prepared to measure electron–positron annihilation cross sections, hadronic and leptonic decay of new particles and monoenergetic photons, as well as to identify particles over a wide momentum range, since the onset of new phenomena in this unexplored energy range will presumably be accompanied by changes in particle composition. (A few smaller experiments will also be possible in the limited space of the North interaction area. Anyone interested in proposing experiments for this area should write to Boyce McDaniel, director of the Laboratory.)

The technique known as "vernier phase-space compression," developed at Cornell, will allow rapid injection of electrons and positrons directly from the synchrotron. Positrons in 60-bunch trains are injected from the linac into the synchrotron, accelerated to 8 GeV, extracted from the synchrotron in a single turn and injected into the storage ring. This process is repeated and the bunches stacked one atop the other within the ring. To coalesce these bunches into a single bunch, vernier compression comes into play. In brief, this technique exploits the existence of a planned size difference equal to one bunch space, between the synchrotron and storage-ring circumferences. The positron bunches are reintroduced into the synchrotron one at a time. Because of the circumference difference, the bunch in the synchrotron catches up with its mates in the storage ring. When the bunch has caught up with the others, it is reinjected into the storage ring, where it merges with one of the bunches there. By this means, all bunches can be coalesced into one within two seconds. The linac for CESR will consist of the original Cornell linac along with components from the dismantled Cambridge Electron Accelerator. With the initial rf power the storage ring will have a maximum energy per beam of 8 GeV, with the option to increase energy to 10 GeV with additional rf power. If funds are approved by this fall, Tigner told us, the turn-on date is scheduled to be October 1979. —MSR ☐