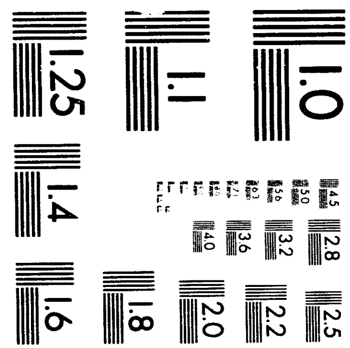
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POWER BEAMING TO SPACE USING A NUCLEAR REACTOR-PUMPED LASER

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Abstract

The present political and environmental climate may slow the inevitable direct utilization of nuclear power in space. In the meantime, there is another approach for using nuclear energy for space power. That approach is to let nuclear energy generate a laser beam in a ground-based nuclear reactor-pumped laser (RPL), and then beam the optical energy into space. Potential space applications for a ground-based RPL include (1) illuminating geosynchronous communication satellites in the earth's shadow to extend their lives, (2) beaming power to orbital transfer vehicles, (3) providing power (from earth) to a lunar base during the long lunar night, and (4) removing space debris. FALCON is a high-power, steady-state, nuclear reactor-pumped laser (RPL) concept that is being developed by the Department of Energy with Sandia National Laboratories as the lead laboratory. The FALCON program has experimentally demonstrated reactor-pumped lasing in various mixtures of xenon, argon, neon, and helium at wavelengths of 0.585, 0.703, 0.725, 1.271, 1.733, 1.792, 2.032, 2.63, 2.65, and 3.37 μm with intrinsic efficiency as high as 2.5%. Frequency-doubling the 1.733-μm line would yield a good match for photovoltaic arrays at 0.867 μm. Preliminary designs of an RPL suitable for power beaming have been completed. The MW-class laser is fairly simple in construction, self-powered, closed-cycle (no exhaust gases), and modular. This paper describes the FALCON program accomplishments and power-beaming applications.

INTRODUCTION

The concept of using nuclear energy to pump a laser has been pursued for almost two decades (McArthur and Tollesfrud 1975, DeYoung et al. 1978, Voinov et al. 1979, Voinov et al. 1990, Hebner and Hays 1990, McArthur 1991, and Hebner and Hays 1992, 1993a, 1993b, 1993c). Recent progress in the FALCON (Fission-Activated Laser CONcept) project (McArthur et al. 1991) at Sandia National Laboratories suggests that a reactor-pumped laser in the 1 to 100 MW regime is technically feasible. This preliminary result needs to be verified with additional prototypic module tests, but if it holds true, then many new processes in the areas of manufacturing, commercial space, and defense may be enabled. The current research program calls for a demonstration of a reactor-pumped module designed to deliver a high-quality laser beam at multi-kilowatt levels for short durations by the end of 1995. This paper describes the accomplishments of the FALCON research program and some potential space applications for reactor-pumped lasers (RPLs).

Nuclear fission is a simple and very concentrated source of energy. About 80% of the energy of fission is contained in the kinetic energy of the fission fragments. The rest of the energy is in gamma rays, neutrinos, neutrons, and radioisotope decay. An RPL utilizes the energy of the various products of fission to excite the laser medium. (See Figure 1). The highly energetic products produce copious secondary electrons which ionizes and excites the laser gas mixture. This creates free electrons which then ionize and excite more atoms. The excited states so created are the source of energy for the lasing process. Different gases slow down the fragments at different rates, and also transfer energy to neighboring atoms at different rates. Lasing requires a balance between excitation of the source atoms and removal of the de-excited states after lasing. Because of this balance, laser efficiency is a sensitive function of fission pump rate, gas mixture, gas temperature, and gas pressure. Numerous experiments over the past several years have mapped out the regimes where reactor-pumped lasing occurs and determined the optimum conditions for lasing at various wavelengths (Hebner and Hays, 1990, 1992, 1993a, 1993b, 1993c).

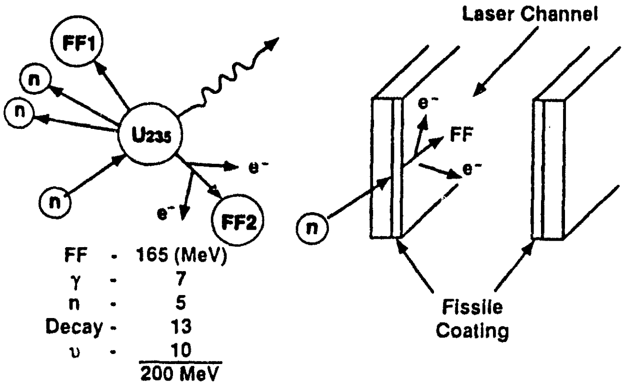

FIGURE 1. Basic Concept for a Reactor-Pumped Laser.

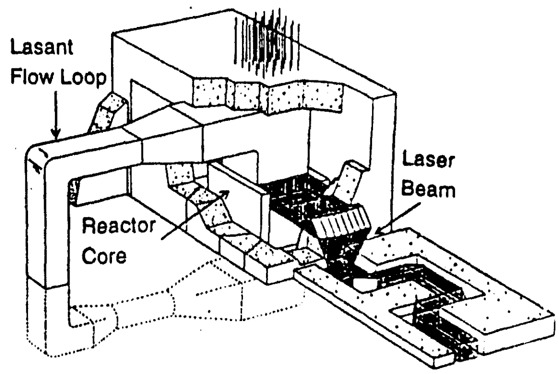

FIGURE 2. Multi-Megawatt FALCON Laser Concept.

Nearly all of the lasers investigated so far have been atomic lasers. That is, the lasing occurs between two states in an atom (typically a noble gas) rather than in a molecule or excimer. Gas mixtures of xenon, argon, neon, and helium have been explored. Table 1 summarizes the wavelengths that have been observed and peak intrinsic efficiencies that have been achieved. (Intrinsic efficiency is the ratio of laser light energy to total energy absorbed by the gas.)

These small-cell physics experiments have mostly involved pulses lasting about 2 ms. The peak power reported has been about 300 W. The parameters involved with the 1792, 1733, and 1271 nm lines were varied fairly widely, so the efficiencies listed are probably close to maximum. Conditions for the other lasing lines were not extensively varied, so their efficiencies could be increased. Voinov et al. (1990) report considerably higher efficiencies for the 585-nm line.

The design of a reactor-pumped laser involves the proper choice of lasing medium, buffer gases, temperature, pressure, flow rate, fuel geometry, heat-removal structures, materials compatible with nuclear operation, critical mass of fuel, reactor moderator, other reactor and neutronics issues, and optical techniques to assure good beam quality. These issues have been addressed over the past several years, and a conceptual design for a multi-megawatt laser has been developed. The reactor, gas flow systems, and heat-removal systems are straightforward and based on existing technology. The optics involve state-of-the art techniques, but essentially all of the required technologies have been demonstrated.

TABLE 1. Demonstrated Wavelengths and Intrinsic Efficiencies for Reactor-Pumped Lasing (Hebner and Hays 1990, 1992, 1993a, 1993b, 1993c).

Lasing Atom	Wavelength (nm)	Intrinsic Efficiency
xenon	3370	>0.1%
xenon	2650	>0.1%
xenon	2630	>0.1%
xenon	2032	2.0%
xenon	1733	2.5%
argon	1792	1.4%
argon	1271	1.1%
neon	725	0.10%
neon	703	0.05%
neon	585	<0.1%

We have developed a conceptual design for a multi-megawatt facility (see Figure 2). The laser consists of the reactor core, a flow loop for the lasant, and extraction optics. The lasant flow loop is closed cycle and contains the noble gases used as the lasant. A primary coolant loop of recirculating D_2O and an open secondary water-cooled loop are used to remove waste heat. The gas flow rate within the lasing region is about 10 m/s which results in little distortion of the laser beam. The reactor is smaller than that in a commercial nuclear power plant, contains considerably less fuel, and operates at near atmospheric pressure. These features make it robust against accidents.

The major strengths of a reactor-pumped laser are (1) continuous, closed-cycle, high-power operation (MW class), (2) simple, modular construction, (3) self-contained power, (4) compact size, and (5) a variety of wavelengths (from visible to infrared). These features make it well-suited for applications that require long-duration operation such as power beaming to space or material processing for industry (for example, cutting, drilling, welding, and surface hardening of metals). In addition, once constructed for long-duration applications, a FALCON laser also can serve for short-duration applications such as high-temperature materials research.

The wavelengths already demonstrated for FALCON are listed in Table 1; more wavelengths are being demonstrated each year. In addition, the FALCON beam is projected to be of high enough quality that its frequency can be doubled with good efficiency. This would yield additional wavelengths at 353, 363, 636, 867, 896, 1016, 1315, 1325, and 1685 nm. Researchers at other laboratories have demonstrated doubling in the infrared at over 50% efficiency in pulsed mode; to achieve high efficiencies at steady state would require focusing the beam and using numerous thin, cooled doubling crystals. A CW doubling efficiency of 20-30% would seem reasonably achievable in the near future. Most of the direct and doubled wavelengths mentioned above propagate well through the atmosphere.

POWER-BEAMING APPLICATIONS

A ground-based RPL can be utilized to beam power into space as an alternative form of "space nuclear power" in case political restrictions delay further development of nuclear reactors in space. These applications are enabled by the recently developed ability to compensate for atmospheric distortion and keep the beam divergence very low as it passes through the atmosphere (Fugate et al. 1991). Another key requirement for a power-beaming application is that the photovoltaic (PV) array operate efficiently at the wavelength of interest. The monochromatic light of a laser leads to high efficiencies in collection arrays (Landis and Westerlund 1992). The efficiency for existing silicon arrays (including the dead space between the solar cells) peaks at around 20% for wavelengths of 700-900 nm (compared to 9% for solar). Future arrays made of GaAs are projected to peak at around 40-50% for similar wavelengths. This suggests that 867 nm (doubled 1733 nm) may be the best wavelength for FALCON power beaming applications.

One commercial opportunity for laser power beaming is to extend the life of geosynchronous satellites by beaming power to them when they are eclipsed by the earth's shadow. (See Figure 3). This application has been proposed by Landis and Westerlund (1992). GEO satellites are eclipsed by the earth's shadow about 90 times per year for durations up to 70 minutes. Batteries normally provide power during these times, but the heavy charge-discharge cycle during eclipses decreases their life expectancy. Battery life, and thus satellite life, could be extended by providing power during eclipses via laser illumination of the photovoltaic array. An advantage of this laser application is that it can tolerate occasional cloud cover or laser outages--the batteries can be relied upon for those instances and the laser beaming will still increase the battery life on the average.

Large mirrors, adaptive optics, and reasonably powerful lasers are needed for this application. There is a tradeoff between mirror diameter and laser power. Calculations indicate that to replace sunlight for a spin-stabilized satellite would require 70 kW at 867 nm on the ground and an 8-m diameter transmission mirror. Alternatively, 275 kW with a 4-m mirror could do the same job. (This assumes a 50% beam loss from atmospheric scattering and absorption at a 45° beaming angle, another 50% loss from uncompensated turbulence, and negligible jitter.)

Since satellites are spaced at about 2° separation, one site could access up to 50 satellites if the beam could be directed over a range of $\pm 50^{\circ}$ (see Figure 3). A single beam could follow one satellite through the earth's shadow (for up to 70 minutes) and then move back to the next satellite entering the shadow at that time. In this manner, one beam could service five satellites if they are separated by about 20° (the width of the earth's shadow at GEO). Up to 10 satellites would be in the earth's shadow at any one time, so many beams would be needed to handle them in the shadow simultaneously. Alternatively, if the battery charging circuits could handle the load, and if the beam could be locked onto target without much delay, perhaps one mirror that switched between satellites could be used. This would result in a shallow discharge of the batteries, but batteries are much more robust against shallow cycles. The commercial payoff is that each satellite could continue earning up to about $25M/year in revenues in the extended-life mode (Landis and Westerlund 1992).

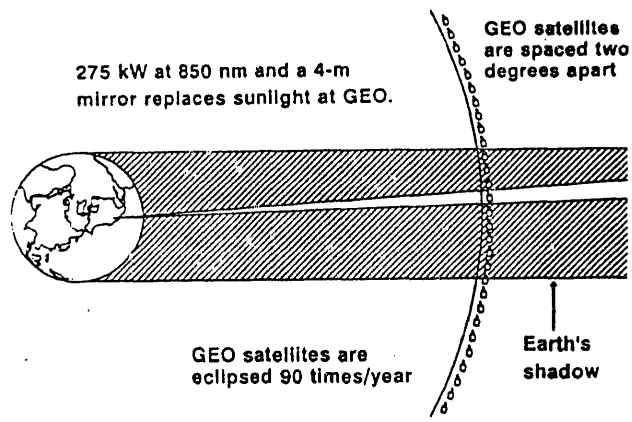

FIGURE 3. Concept for Beaming Power to Geo-Synchronous Satellites in the Earth's Shadow.

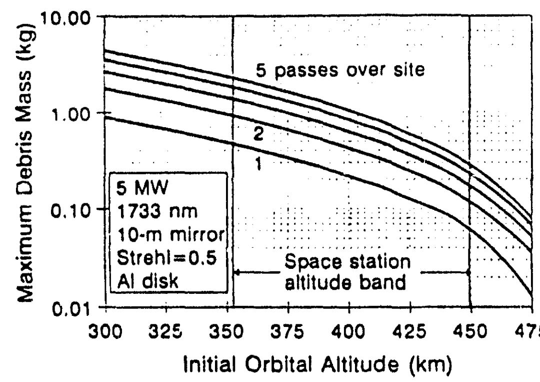

FIGURE 4. Size of Space Debris Which could be Removed by a Ground-Based Laser.

Laser illumination also could augment solar power to increase the power available to new satellites designed for power beaming. Increased power could boost the signal strength or allow more channels on the satellite. In addition, high-frequency channels (which require higher power to penetrate the atmosphere) could be used. Removal of waste heat from the satellite limits the amount of power that can be transmitted. But even with this limitation, a spin-stabilized satellite with power beaming could generate 0.9 kW/m^2 of the electrical power, which is six times that of an equivalent conventional satellite using the same size solar panel (Morgan and Lipinski 1993). A 3-axis stabilized satellite could generate 0.6 kW/m^2 (four times conventional). Because the satellite is dependent on the laser power in this mode, laser downtime must be minimized by having multiple sites, or applications which can tolerate outages must be found.

Another application for power beaming is to provide propulsion power for orbital transfer vehicles (OTVs) that deliver a satellite from low earth orbit (LEO) to geosynchronous orbit (GEO). The payload for an OTV can be increased by a factor of four if an ion-thruster is used with power-beaming to the thruster (Ponikvar 1991). Alternatively, the laser could be reflected off a lightweight collector on the OTV and focused on a heat exchanger for direct heating of hydrogen fuel This, in essence, would be a high-power version of a solar-thermal rocket. The laser power needed for these applications is a few hundred kW and it need not be continuous. The high orbit of an OTV would allow it to be seen for about 25% of the time during the orbit, so a single site could do the job. Occasional outages due to weather could be tolerated. An additional category for laser propulsion is launch from earth into orbit (Lawrence et al. 1991). This application is more far term since it is calculated to require about a MW of laser beam for each kg put into low-earth orbit.

Power beaming to the moon also is an attractive option for a lunar base because the moon is accessible about 25% of the time. The advantage of power beaming over lunar solar power is in the savings in energy storage for the 354-hour lunar night. The mass of such storage is over 10 times that of the photovoltaic system (Fay et al. 1991). Power beaming may be the enabling technology for a lunar base if safety and space-testing concerns delay the approval of a lunar nuclear power plant.

Space debris is becoming more of a concern for space assets, especially for the space station where human life is involved. A ground-based laser could remove the debris by ablating the surface and causing a retarding thrust. The debris would then re-enter the atmosphere and burn up in half an orbit. The beam intensity must be high enough to overcome thermal radiation and reach vaporization temperature. This technique is probably the most effective available for debris removal in terms of cost or energy usage, but it would require a 10-m diameter mirror that could track the debris for 30 seconds or more (Monroe 1993). A 5-MW laser could remove debris from the orbital altitude of Space Station Freedom. Figure 4 shows the maximum size of debris that can be de-orbited vs. altitude for a given number of passes over the laser site. The debris is assumed to be 0.5-cm thick aluminum (fragmented rocket bodies), which is the most common component. Debris as small as 5 cm diameter (about 0.03 kg) can be tracked and has been catalogued. Figure 4 shows that debris up to about a kilogram can be de-orbited in a few passes overhead. This category makes up the most numerous portion of the threat.

DUAL-USE APPLICATIONS

Besides "space nuclear power" applications of a ground-based RPL, the facility would have several dual-use applications. The laser could develop and implement high-temperature laser material processing at power levels 10-100 times what is available today. (Present day industrial lasers are all under 50 kW in the 10-μm regime, and under 5 kW in the 1-μm regime.) Potential applications for a high-power RPL include (1) single-pass deep-penetration welding and cutting of thick structures (especially aluminum) such as aircraft structures, deep-sea drilling structures, or reactor pressure vessels, (2) wide-area, uniform application of tungsten carbide and other claddings to metal by melting powders onto the surface, (3) clean, controllable vapor deposition of ceramics onto metal surfaces for high-temperature insulation or surface hardening (avoiding impurities associated with traditional plasma sources), (4) production of diamond-like coatings over wide areas for scratch protection, and (5) ceramic lithography, in which complex 3-D structures are built up by sintering layers of ceramic powders using the beam to sinter the contour at each level.

An enabling feature for utilizing an RPL for material processing is the fact light between 0.5 and 1.9 μm can be transported fairly efficiently in fiber optics. For example, a 2.4-kW 1.06-μm beam has been transported 150 m in a 1-mm diameter fiber with only 10% loss (Filgas 1992). So one could envision an industrial park established a few miles from the RPL. The laser light would be directed through a vacuum conduit with negligible loss to the industrial park. Once at the park, the light would be multiplexed through a network of fiber optics to the various work stations.

Present lasers typically can weld up to 1/4-inch steel. To weld or cut steel or aluminum that is over an inch thick at reasonable speeds requires a laser in excess of 100 kW (Bransch 1992). The market for thick welds or cuts includes ships (commercial and Navy, construction and disassembly), off-shore oil-well drilling platforms, aluminum aircraft frames, and bridges. Many of these markets could be reached by an RPL on a ship with a fiber-optic delivery system.

Lasers can be used to apply cladding to the surface of metals to increase their hardness and wear resistance (Volz 1992). A powder of tungsten carbide or other material is laid down on the surface, and the beam melts the surface of the metal. This process is done today with 1/4-inch diameter beams that paint their way across surfaces in narrow strips, which is slow and often results in residual stresses that reduce the wear-resistance of the cladding. A very high-power beam would allow a much broader, more uniform application of the cladding. The market for cladding includes cams on automotive camshafts, the wheel-bearing portions of axles, railway wheels, steam turbine blades, ship propellers, large valve seats, and catapult tracks on aircraft carriers.

Ceramics can provide good high-temperature insulation when they are applied to the surface of metal structures by vapor deposition. Vaporization using a laser beam inside a vacuum chamber can avoid harmful impurities, and the same beam can be used to melt and smooth the resulting layer. Laser power in the 100-kW regime and higher allows reasonable deposition rates (Tsukamoto et al. 1990). The potential market for ceramic deposition includes high-temperature turbine blades and internal combustion engine parts that would increase overall efficiency.

Deposition of diamond-like coatings requires vaporization of a carbon source at high intensity to avoid formation of graphite. This involves typically 10^{11} W/cm^2 at 1 μm wavelength, or 10^8 W/cm^2 at 0.25 μm. Typically this has been achieved by tightly focusing a very short pulse NdYAG laser (Martin-Gago et al. 1992). An RPL may be able to achieve similar results with high-power focusing, only moderate pulse compression, and possibly frequency doubling to reduce power requirements and minimize the production of contaminant forms of carbon. Markets include coating eyeglasses and aircraft windows to prevent scratching.

Three-dimensional stereo lithography is an existing technology in which a laser creates complex structures in plastic. A thin beam is scanned across the surface of a special liquid polymer in a specified pattern causing it to solidify where it is irradiated. Another thin layer of liquid is added, and the scanning beam solidifies another layer on top of the first in a slightly different shape. Contour levels are built up this way until a finished product results and the remaining liquid is drained away. This same process could be used to sinter ceramic powders into shapes that could not be machined. The enabling technology here is a laser powerful enough to overcome the radiative heat loss at the sintering temperature. The market for this area needs to be developed, but could include all-ceramic automotive, jet, and rocket engine parts for higher-temperature operation.

SUMMARY

Steady progress in nuclear reactor-pumped laser technology by the DOE over the past decade has advanced the technology to the point where a large-scale RPL with good beam quality appears to be feasible. This preliminary conclusion needs to be verified with additional tests using larger prototypic modules, but if it holds true, then many new processes in the areas of manufacturing, commercial space, and defense may be enabled. (The current research program calls for a demonstration of a reactor-pumped module designed to deliver a high-quality laser beam at multi-kilowatt levels for short durations by the end of 1995.). Potential space applications for a ground-based RPL include power beaming to geosynchronous communication satellites, orbital transfer vehicles, and a lunar base. Space debris removal is also possible. Dual-use applications include material processing for industry.

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