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ABSTRACT

Power beaming is the concept of centralized power generation and distribution to remote users via energy beams such as microwaves or laser beams. The power beaming community is presently performing technical evaluations of available lasers as part of the design process for developing terrestrial and space-based power beaming systems. This report describes the suitability of employing a nuclear reactor-pumped laser in a power beaming system. Although there are several technical issues to be resolved, the power beaming community currently believes that the AlGaAs solid-state laser is the primary candidate for power beaming because that laser meets the many design criteria for such a system and integrates well with the GaAs photodiode receiver array. After reviewing the history and physics of reactor-pumped lasers, the advantages of these lasers for power beaming are discussed, along with several technical issues which are currently facing reactor-pumped laser research. The overriding conclusion is that reactor-pumped laser technology is not presently developed to the point of being technially or economically competitive with more mature solid-state technologies for application to power beaming.

Application of Reactor-Pumped Lasers to Power Beaming

1. INTRODUCTION

Power beaming is the concept of centralized power generation and distribution to remote users via energy beams such as microwaves or laser beams. Although the concept has terrestrial applications, interest in power beaming stems mainly from its utility in space-based applications where several power generating satellites in high orbit could supply power to a larger network of users such as satellites, orbital transfer vehicles (OTV's), and space colonies. By replacing the current method of employing onboard power generation systems with every space mission with a new space power infrastructure based on power beaming, the power requirements for space exploration, colonization, and exploitation can be fulfilled more economically than with solar power systems or chemical OTV's (see Figure 1).

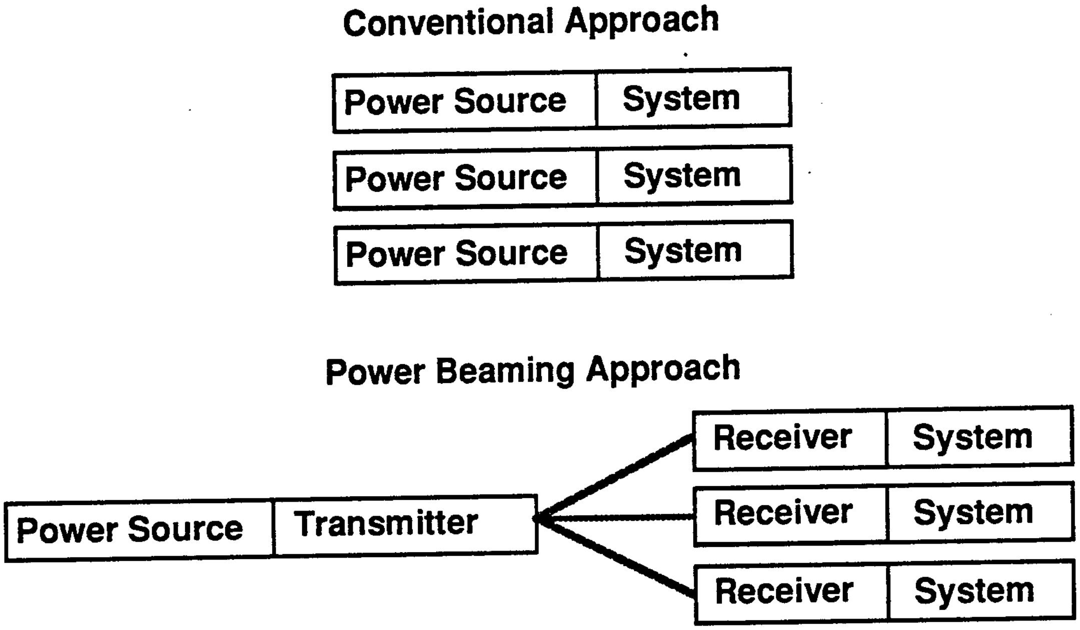

Figure 1 - Schematic of conventional and power beaming architectures.

Since power availability is critical to national space programs, several national agencies and laboratories have sponsored research into power beaming as a support program for the planned space station, lunar base, and manned Mars mission. In the late 1970s, the National Aeronautics and Space Administration (NASA) and the U.S. Department of Energy (DOE) sponsored the Solar Power Satellite (SPS) program whereby a network of satellites would convert solar energy to microwaves or laser beams and beam it down to receivers on the ground (DOE78a, DOE78b). The SPS program showed the power beaming concept to be feasible but not economically competetive (DOE80).

More recently, Pacific Northwest Laboratory (PNL) has been authorized to direct the national research effort in power beaming as a supporting technology for the Strategic Defense Initiative (SDI) and the Space Exploration Initiative (SEI). PNL has conducted research and coordinated the efforts of groups at the Idaho National Engineering Laboratory (INEL), the NASA Lewis Research Center (LeRC), and other government and commercial laboratories. Both PNL (PNL91) and NASA (DeY89) have sponsored power beaming workshops. The DOE-SEI $30M budget request for FY 1992 does include power beaming research and is expected to increase in the coming years (Wid91).

1.1 Demand for Power Beaming

Since near-Earth space is relatively undeveloped, there is a relatively wide range of options for establishing the infrastructure for expansion into the solar system. Power beaming is seen as an important part of that system by providing for future power needs on Earth and in space. Terrestrial needs are relatively straightforward; a network of satellites around the planet could generate power and distribute it to parts of the planet where demand is high. Power could also be generated on the ground and beamed to these satellites for distribution or used to provide thrust for launch vehicles or OTV's.

The space-based demand for power beaming is more open-ended than the terrestrial demand since the space power network is essentially nonexistent. While power beaming could only augment the already extensive terrestrial power grid, it could be the backbone of the space power network. Table 1 indicates the power requirements for various space activities and equipment (collected from various sources in PNL91). Note that the SP-100, NASA's proposed baseline power reactor satellite, is designed to provide 1000 kWe to its own power beaming components whose efficiency will reduce the actual power available to user satellites. PNL's power beaming concept envisions a constellation of 12 power satellites providing power to roughly 100 user satellites (PNL90).

Note that NASA and the space community anticipate space exploration to be a continued national priority so that a lunar base will be established around the year 2010 and a manned Mars mission will occur 10 to 20 years afterward.

Utilization	Power Requirement (kWe)
Life support per Lunar Base Crewmember	3
Lunar rovers, haulers, excavators	3 - 40 (mission enabling)
GEO Satellite N/S Stationkeeping	7
GEO Satellite operation	10 - 40
MPD thruster for OTV	200 - 250
Space Station Freedom	56 short term 250 long term
Initial Lunar/Mars exploration	50 - 200
Initial Lunar Base	100 - 500
Lunar Settlement	500 - 1000

Table 1 - Power requirements for various space-related equipment and activities (PNL91).

In addition to supplying power for activities on planetary bodies, power beaming can provide thrust for satellites (enabling them to remain on-station for longer periods), probes, and electric-powered OTV's (Pon91, PNL90) for payload boosting from LEO to GEO. Although the thrust imparted to a space vehicle by power beaming is less than that provided by a chemical rocket, the vehicle's resupply mass is far less so that operating costs are reduced (Cot91). Power beaming can also serve commercial interests in space by providing power for orbital manufacturing and laboratory complexes.

Several government agencies are natural customers for beamed power. The Strategic Defense Initiative Office (SDIO) would use the beamed power itself for military purposes, while the Department of Defense (DOD) has military satellites which could be supported by a power beaming network. NASA and the National Oceanographic and Atmospheric Administration (NOAA) also operate space assets which would benefit from such a network.

1.2 Available Laser Technologies

PNL has assessed the various technologies competing for the laser power beaming system (PNL90). Tables 2 and 4 list their criteria for ranking laser systems and power converters (receivers) which are based on the tradeoffs associated with the conceptual design of a 1000 kWe source for the laser system such as would be available with the SP-100 reactor. Tables 3 and 5 contain PNL's rankings of the available laser systems and power converters based on these criteria; any laser type with two or more unacceptable ratings (1's in Table 3) was dropped from consideration for inclusion in their prototype power beaming system.

Criteria	Acceptable (3)	Possibly (2)	Unacceptable (1)
Wavelength	< 0.4 µm	2.0 to 0.4 µm	> 2.0 µm
Efficiency	> 25 %	15 to 25 %	< 15 %
Voltage	< 1 kV	1 to 25 kV	> 25 kV
Size	0.1 m^3	0.1 to 1.0 m^3	> 1.0 m^3
Weight	Dominated by gain medium	Some heavy structures	Many heavy elements
Lifetime	20 x 10^3 hr	2 to 20 x 10^3 hr	< 2 x 10^3 hr
Vibration	None	Some	Continuously rotating machine
Effluents	None	Innocuous gases	Corrosive gases
Power Scaling	Natural - only thermal limit	Natural - limited by size, voltage	Will not scale
Complexity	Simple or all long-life elements	Moderate, possibly one or two issues	Complex, many critical issues

Table 2 - Criteria for use in ranking laser systems for power beaming (PNL90).

Criteria	Crystalline	Laser Diode	Excimer	Metal Vapor	Molecular
Example	Nd:YAg	AlGaAs	XeCl	Copper Vapor	CO_2
Wavelength	2	2	3	2	1
Efficiency	2	3	1	1	2
Voltage Required	3	3	1	2	2
Size	2	3	1	1	1
Weight	2	3	1	2	2
Lifetime	3	3	1	2	2
Vibration	2	3	1	2	2
Exhaust product	3	3	1	3	2
Power scaling	2	3	2	1	2
Complexity	2	3	1	2	2
Total	23	29	13	18	18
Comments (maturity)	Depends on a diode pump	Large arrays yet to be built	Major effort underway	Isotope separation development	Weapons technology

Table 3 - Laser System Technology Assessment (PNL90).

Criteria	Acceptable (3)	Possibly (2)	Unacceptable (1)
Wavelength	matches laser	close	inappropriate
Efficiency	> 50 %	20 to 50 %	< 20 %
Size	< collector	≈ collector	> collector
Weight	< collector	≈ collector	> collector
Lifetime	> 20×10^3 hr	2 to 20×10^3 hr	< 2×10^3 hr
Vibration	No mechanical motions	Some mechanical motions	Continuously rotating machinery
Power Handling	> 1 MW	0.1 - 1.0 MW	< 0.1 MW
Complexity	Simple	Moderate, possibly one or two issues	Complex, many issues
Maturity	well understood	technical demonstrations	conceptual

Table 4 - Criteria for use in ranking laser power converter technologies (PNL90).

Criteria	Photo-voltaic	Heat Engine	MPD	Thermo-electric	Therm-ionic	Photo-chemical	Reverse FEL	Optic Diode
Typical type	GaAs	Mechanical	Plasma	Semi-conductor	Cesium	NOT ENOUGH IS KNOWN FOR PROPER EVALUATION		
Wavelength	3	3	3	3	3			
Efficiency	3	3	3	1	2			
Size	3	3	3	3	3			
Weight	3	2	2	3	3			
Lifetime	3	2	2	3	2			
Vibration	3	0.5	3	3	3			
Power handling	3	3	3	3	3			
Complexity	3	2	1	2	1			
Maturity	2	3	1	2	2			
Total	26	22.5	21	23	22			

Table 5 - Laser System Technology Assessment (PNL90).

These tables demonstrate PNL's rationale for choosing their prototype power beaming transmitter-receiver system to be the AlGaAs solid state laser operating at 0.833 μm connected to a tuned GaAs photovoltaic cell. Solid-state lasers and photovoltaic arrays (PVA's) are the leading candidates for power beaming systems and thus dominate the current literature in power beaming system architectures.

System efficiency is estimated as 20%, which is the product of the AlGaAs laser efficiency (50% expected in the next 10-15 years), the transmitter optical efficiency (80% expected due to minor losses in transmission optics), the collection efficiency (only the main lobe of the transmitted gaussian beam containing 85% of the total beam energy will be collected), and the GaAs receiver efficiency (60% expected in the next 10-15 years). Thus, the efficiency of this system depends on future advances in solid state laser and collector efficiency; with the current design, only 200 kWe of the SP-100's 1 MWe power output will be available to user satellites.

Other laser technologies such as free electron lasers (FEL's) are still being explored. FEL advantages include: relatively high wall plug efficiency (35%), wavelength tunability, lower sensitivity to temperature fluctuations than PVA's, high power operation, and no gas handling requirements. Unfortunately, FEL research and development is still relatively immature. At this point, they have not been optimized for weight minimization, their operation at high power is limited by beam scrapeoff, and they are inefficient at the near-optical wavelengths that the power beaming community would like to use.

1.3 Technical and Social Issues

There are a many technical and societal obstacles which must be overcome in the coming decades if the power beaming concept is to be successful. Among these issues are:

- Beam quality and pointing accuracy. Transmitting power beams over large distances requires extremely precise beam conditioning and pointing. The quality of the beam emitted by an array of solid state lasers is essentially determined by the degree to which one can control the phases of the array elements; the phases must combine coherently for enough of the beam's energy to arrive at the receiver. Development of these phased arrays is crucial to the power beaming concept. Pointing accuracy must be achievable to within 0.05 microradians for the long distances between power satellites and user assets, which eliminates the option of mechanical beam steering. These areas are the subject of intense research in this country.
- Environmental and health physics. The environmental impact of beaming power either to or from the Earth has yet to be determined. Zones of exclusion may have to be established around

receiver stations on the ground and in the airspace above, and any potential hazards from beam scatter in the atmosphere must be evaluated. There is some uncertainty as to the OSHA safe power levels for exposure to microwave beams. Space applications carry similar concerns for human exposure but environmental impacts are lessened.

- Atmospheric losses and weather. Bad weather (rain, snow, smog, dust) significantly attenuates a transmitted power beam; even clear weather atmospheric transmission is only 80% efficient. These problems may be overcome by advances in adaptive optics which can compensate for atmospheric distortions.
- Solid state research. As stated above, solid state laser and receiver arrays are the leading candidates for power beaming but need to be further developed. Their efficiency, lifetime, susceptibility to damage from dust, and temperature stability need to be significantly improved before power beaming goals can be achieved. A great deal of research is being performed in these areas.
- System studies. There are many tradeoffs in designing a power beaming architecture, some of which are: efficiency, mass, development and operation costs, lifetime, reliability, availability, and maintenance. Assigning weights to each aspect is complicated by the need for more research in several key technologies and the interdependence of the various system elements. (Development of an extremely efficient laser, for example, is not useful to a power beaming system if the laser has an unreasonably high mass or if its wavelength cannot be efficiently converted to electricity by a photovoltaic receiver or if the its reliability is so low that the overall system availability falls below specifications.) System studies have been performed on power beaming architectures, but it is crucial to understand the caveats involved and the uncertainties in the numbers which are generated. Many of the numbers used in system studies (mass, efficiency, cost, availability) are projections of future capabilities and have yet to be realized.

Note too that the weights given to each system aspect depend on the system's mission, which is unclear at this point and is likely to remain unclear given the current economic, social, and political situation in the U.S. and the world.

- Economics. A space power beaming infrastructure will not be built if it is not shown to be economically competitive with the current technique of using onboard power supplies for each space asset. The aerospace industry is understandably hesitant to risk hundreds of millions of dollars by embracing untried technologies. Current estimates for the overall cost of establishing a power beaming network are tens to hundreds of billions of dollars.
- Politics. Power beaming is often seen as a technology which will require an international effort to develop and sustain because of its high cost and its application to international power needs

on a global scale. A terrestrial power beaming network would require six to ten sites spaced around the globe, which guarantees the need for international cooperation. International access to and exploration of space also mandates international control of power availability in space.

Perhaps the greatest liabilities facing power beaming are the currently strong antinuclear sentiment in the U.S. and the perceived need to spend tax dollars "at home" instead of in space. The American public does not embrace nuclear power or feel the need to spend money to alleviate long-term problems such as power availability. NASA's recent string of technical problems has severely damaged its public reputation; the agency no longer enjoys the Congressional support that it did in the Apollo era and will have a difficult task in obtaining the level of funding envisioned by the power beaming community.

2. REACTOR-PUMPED GAS LASERS

2.1 History

The idea of pumping a laser with a nuclear reactor was first concived in U.S. and most of the developmental work has been performed in this country. The first theoretical study of a direct He-Ne reactor-pumped laser (RPL[1]) was made by Herwig in 1964 at United Aircraft Labs (Her64), followed by more theory on He-Ne and experiments on CO_2 by DeShong at Argonne National Laboratory (ANL) (DeS65,DeS68). McArthur and Tollefsrud (McA75) demonstrated the first RPL with CO at Sandia National Laboratory (SNL) in 1975.

After McArthur's demonstration, there followed a period of development at many laboratories where new gas mixtures and geometries were tried and laser power scaling with energy deposition, neutron flux, and lasing gas pressure were examined with the goals of developing shorter

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[1] Note that some (Mil89b) would differentiate between a "reactor-pumped" laser where energy is deposited in the laser medium by fission fragments and a "nuclear-pumped" laser where energy is deposited by the products of neutron capture reactions in ^{3}He or ^{10}B. This report will refer to both pumping methods as "reactor-pumping" and both types of lasers as "reactor-pumped lasers" or RPLs. Gamma-ray lasers pumped by nuclear explosions were demonstrated by LLNL (Ebe74) and LANL (Lyo74) but their uncontrolled nature puts them outside the scope of this report. Solid-state reactor-pumped lasers are degraded by radiation damage and are not as suitable for power beaming as reactor-pumped gas lasers.

wavelength lasers, lower neutron threshholds, and improved efficiencies. NASA Langley Research Center (Jal83) had perhaps the most extensive effort in this stage and subcontracted to other labs. As an outgrowth of the programs to develop the nuclear-powered rocket and gas core nuclear reactor, NASA's goals were to demonstrate high power output (1 kW) from an RPL and to investigate gaseous uranium in the laser mixture. Other notable contributions were made by the University of Illinois Laboratory Microfusion Facility (Mil89a), the University of Florida (Row81), Northrop Laboratory (Eer66, Dav68), SNL, and Los Alamos National Laboratory (LANL) (Hel75).

During the 80's, the leading experiments were performed on FALCON (Fission Activated Laser Concept) using the Sandia Pulsed Reactors II and III (Hay86, McA87, McA88, Min87, Alf89, Pic91a, Pic91b) and on the INEL Centaurus project with the TREAT pulsed reactor. The University of Illinois provided valuable chemical kinetics modeling for both groups (Ohw89, Mor88). The University of Missouri promoted an aerosol reactor nuclear-pumped flashlamp known as the Aerosol Reactor Energy Conversion System (ARECS) (Pre84,Pre88).

Current experimental work at SNL and INEL involves the development and application of sensitive diagnostics for RPL's using tunable probe lasers for measuring small signal gain, saturation intensity, laser cavity losses, and relevant plasma parameters such as temperature, density, index of refraction, and flow speed. Computer modeling continues in chemical kinetics and fluid dynmics, particularly with regard to wavefront distortion in a heated gas medium. Supporting experiments involve chemical reaction rate measurements, resonator cavity design, and research into adaptive optics and radiation effects on laser cavity optical components.

2.2 Technical Details

A nuclear reactor can pump a laser through capture of thermal neutrons in the laser medium. The captured neutrons may trigger radioactive decay of the absorber or may induce fission; both processes release energetic charged particles into the laser gas which then pump the gas to lase.

Most RPL experiments can be further divided into wall or volumetric pumping schemes (see Figure 2.) In wall pumping, the thermal neutrons are absorbed by a solid coating which lines the interior of the laser cavity. After the neutron absorption results in decay or fission, the energetic reaction products slow down in the laser gas, depositing energy through collisions with the gas atoms. The neutron absorber is typically either ^{10}B or an enriched uranium oxide which have the following neutron absorption reactions:

$$^{10}B + {}^{1}n \rightarrow {}^{4}\alpha\ (1.46\ \mathrm{MeV}) + {}^{7}Li\ (0.84\ \mathrm{MeV})$$
$$^{235}U_xO_y + {}^{1}n \rightarrow ff\ (\sim 65\ \mathrm{MeV}) + FF\ (\sim 97\ \mathrm{MeV})$$

Here, U_xO_y is typically U_3O_8 or UO_2, and fission fragments are represented by ff and FF.

The advantages of wall pumping include the control over the location and strength of the energy deposition and the high energy deposition achievable with the fission fragments produced by ^{235}U absorption. However, wall pumping can be inefficient because the reaction products have limited range in the laser gas and can nonuniformly pump the laser optical cavity. The products are also released isotropically in the wall so that only 50% of the reaction products are born with the correct velocity toward the laser. Of these, more than half of the remaining kinetic energy will be absorbed in the wall thickness before the particles even reach the laser gas.

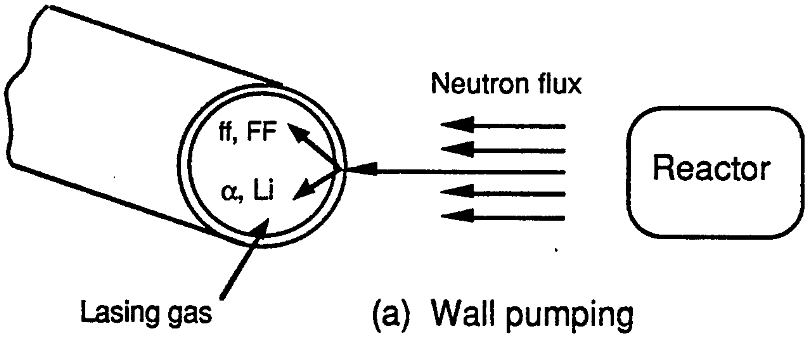
In volumetric pumping, the thermal neutrons are absorbed in the laser medium by gaseous absorbers. Again, after neutron absorption, the energetic reaction products slow down in the laser gas and pump it to lase. The neutron absorber is most often ^{3}He, although some work has been performed with gaseous $^{235}UF_6$ (Rod79, DeY80a, Wil78):

$$^{3}He + n \rightarrow {}^{1}H\ (0.57\ \mathrm{MeV}) + {}^{3}H\ (0.19\ \mathrm{MeV})$$
$$^{235}UF_6 + n \rightarrow ff\ (\sim 65\ \mathrm{MeV}) + FF\ (\sim 97\ \mathrm{MeV})$$

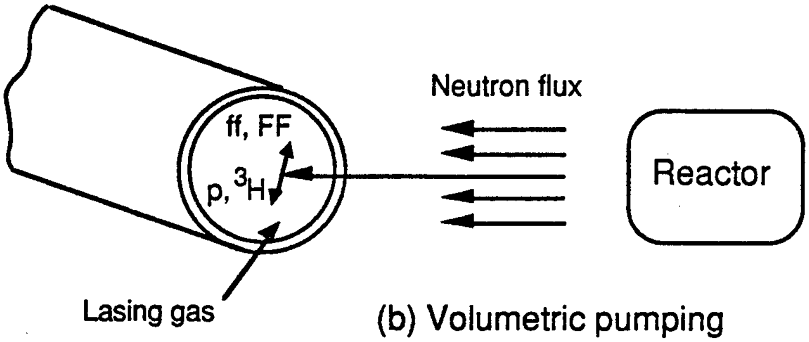
The major advantages to the volumetric scheme are its more uniform pumping of the optical cavity and the beneficial chemical kinetics of helium in the laser mixture. However, there are problems caused by the use of buffer gases. The volumetric fission option is not commonly used since the fluorine in $^{235}UF_6$ is detrimental to the chemical kinetics; it absorbs free electrons, quenches the upper laser level, and strongly absorbs laser photons below 400 nm in wavelength. Even ^{3}He is not entirely beneficial; it absorbs neutrons so strongly that reactor criticality can be endangered. In addition, there are difficult engineering issues related to the fluid dynamics of such a flowing hot gas in the reactor.

There is still much debate over the relative merits of wall and volumetric pumping; both seem to have complementary strengths and weaknesses. Most of the lasers listed in Table 6 below have been pumped with both methods.

Note that in both wall and volumetric pumping experiments, the laser gas can be static or be flowed through the optical cavity. Static systems avoid the engineering problems associated with flow, but can produce excessive gas heating. Flowing systems can achieve high laser power by constantly refreshing the optical cavity with unsaturated, "high-gain" gas.



(a) Wall pumping



(b) Volumetric pumping

Figure 2 - Direct reactor-pumping schemes, after Jalufka (Jal83). The laser cavity need not be external to the reactor.

Note that in both wall and volumetric pumping experiments, the laser gas can be static or be flowed through the optical cavity. Static systems avoid the engineering problems associated with flow, but can produce excessive gas heating. Flowing systems can achieve high laser power by constantly refreshing the optical cavity with unsaturated, "high-gain" gas.

Many RPL experiments have been performed using a fast burst reactor, a relatively small, portable device which is unshielded and uncooled and produces peak fast neutron fluxes of 2 x 10^{17} neutrons/cm^{2}sec in a 200 μs FWHM pulse. Although the fast reactor pulse is not steady-state, the laser output closely follows the thermalized neutron pulse, which leads to the conclusion that lasing would be steady state if the thermal neutron flux were constant. Since the reactor heats up and must be allowed to cool for roughly two hours before the next shot, these reactors are limited to arond five shots per day. A polyethylene moderator is required to slow the fast neutrons down to thermal speeds. The reactor's portability allows for easy access to the laser cavity after each shot; the two can be separated and the laser examined while the reactor cools down.

Thermal TRIGA-type reactors have also been used in RPL experiments, but the laser apparatus must be placed in a neutral beam port and becomes radioactive and thus not accessible once placed in the reactor. These reactors can be operated in pulsed mode with peak neutron fluxes of 5×10^{15} neutrons/cm^{2}sec in a 12 ms FWHM pulse at a rate of three pulses per hour.

Nuclear-driven flashlamp lasers are two-cell systems where neutrons are captured in a flashlamp cell which fluoresces and photolytically pumps the laser cell (Pre88). The perceived advantage of this system is that the laser gas does not heat up because energy is not deposited in it (any Helium in the laser cavity would presumably be ^{4}He which does not absorb neutrons as strongly as ^{3}He. See Section 2.5 for a discussion of the detrimental effects of gas heating.) However, flashlamps lose efficiency due to geometric losses and are not the major focus of experimental research at this time. Prelas (Pre84, Pre88) has proposed using fissile aerosols in the flashlamp cell as a high-efficiency non-reactive alternative to volumetric pumping, but the concept has not received recent DOE support to the extent of the other methods being investigated at SNL and INEL; there are uncertainties in power deposition due to nonuniform aerosol flow and in reduced photon extraction efficiency due to increased gas opacity and the complicated geometry of a two-cell system.

2.3 Advantages for Power Beaming

The advantages RPL's have in a space power beaming system are:

- They are compact, self-contained devices which require little maintenance and can run for long periods without refueling.
- They provide high power (1 - 100 MW) at steady state which scales with large laser cavity volumes, limited only by neutron transport and fluence.
- They are not tied to one specific wavelength; changing the operating wavelength would only require changing the lasing gas mixture and associated optics.
- They convert energy directly from reactor-produced fission fragments to atomic excited states in the laser medium. There are no intermediate steps wherein fission fragments heat a fluid which spins a turbine which produces electricity which breaks down a gas which produces the atomic excited states.

2.4 RPL's Demonstrated

When fission fragments slow down in a gas, the resulting fluorescence spectrum is similar to that produced by electron beam excitation; thus, many RPL's have also been pumped by relativistic electron beams and discharges (DeY80b). Table 6 lists various RPL's which have been demonstrated to date, including gas mixture, wavelength, and pumping method. Nearly all of these experiments were proof-of-principle studies and made no effort to optimize the laser efficiency or output intensity with neutron flux or reactor geometry, although most performed sensitivity studies for gas pressure and mixture.

Laser [Gas Mixture]	Wavelengths (μm)	Wall (W) or Volume (V) Pumping	References
XeF [^{3}He-Xe-NF$_3$]	0.3510	V - ^{3}He	Hay86
CdII [^{3}He-Cd]	0.5337, 0.5378	V - ^{3}He	Jal83, Mis80
Ne [^{3}He-Ne-Ar]	0.5853	W - ^{235}U	Heb90
HgII [^{3}He-Hg]	0.6150	W - ^{10}B	Ake77
Ne [^{3}He-Ne]	0.6328	V - ^{3}He	Jal83, Car80, others
N [Ne-N$_2$]	0.8629, 0.9392	W - ^{10}B	DeY76
CO [^{3}He-(CO/CO$_2$)-N$_2$]	1.45, 5.1 - 5.6 vibrational	W - ^{10}B W - ^{235}U V - ^{3}He	Pre77 McA75 Jal83
Cl [^{3}He-Cl$_2$]	1.587	V - ^{3}He	Jal83, DeY78
Ar [^{3}He-Ar]	1.79, 1.27	V - ^{3}He	Jal83, DeY78
[^{4}He-Ar]	2.397, 1.19, 1.15	W - ^{235}U	Voi79
Kr [^{3}He-Kr]	2.52, 2.19	V - ^{3}He W - ^{235}U	Jal83, DeY77, DeY78 Voi79*
Xe [^{3}He-Xe]	2.03, 2.48, 2.63, 3.51, 3.65	V - ^{3}He W - ^{235}U	Jal83, Hel75, DeY77, DeY78, DeY80a, Jal81, Man77 Voi79*
Xe [^{3}He-Ar-Xe]	2.03	V - ^{3}He	Alf89
Xe [Ar-Xe]	1.73, 2.48 2.63, 3.11	V - ^{3}He	DeY80a, DeY81, Alf89

* Note Voi79 used ^{4}He but often observed the same laser wavelengths associated with ^{3}He.

Table 6 - Demonstrated Reactor-Pumped Lasers

While recent work in the U.S. has centered on the Xenon infrared lasers (Alf89), it is a misconception that nuclear reactors are incapable of pumping the visible wavelength lasers favored by many in the power beaming community (indeed, there is no clear wavelength consensus yet; solid state receivers sensitive to 1.3 μm are being considered for power beaming systems.) Note in Table 6 that not all wavelengths associated with a particular laser were observed by each reference; most experiments are optimized to monitor only one or two wavelengths for evidence of lasing.

2.5 Technical Issues

There are several technical difficulties which must be overcome before an RPL can be considered as a viable candidate for a power beaming system: gas heating, kinetics, and system analysis.

2.5.1 Gas Heating

Nonuniform power deposition in the laser cavity causes nonuniform gas heating which leads to pressure and index of refraction gradients in the gas (Neu90, Mon91, Alf89, Tor89, Tor90). These gradients defocus the laser beam and can actually terminate the laser (Tor90,Cor91). This problem is more serious for wall pumping using fission fragments than it is for volumetric pumping because of the short slowing down range of the fission fragments in the laser gas. Decreasing the cavity volume partly alleviates this problem and results in better beam focusing because of the smaller aperture, but also reduces the laser power.

2.5.2 Chemical and Neutron Kinetics

Optimizing laser performance involves understanding the laser's chemical kinetics. Originally, the dominant excitation mechanism was thought to be direct excitation from ground to the upper laser level via collisions with the products of the neutron capture reaction (Jal81). Eventually, this concept was replaced by a collisional-radiative recombination model where the neutron capture products ionize the gas and create free electrons which recombine into highly excited states of the lasant atom, which then cascade downwards to populate the upper laser level (Rus71, Has79, Wil79). Recombination from excimer ion dissociation also feeds this cascade process.

The chemical kinetics of RPL's are extremely complex for several reasons:

- The dominant excitation pathways vary with the pressure, power deposition and gas mixture.
- Many important reaction rates (and their temperature dependences) have not been measured; there are also many reactions which are not directly connected to the laser levels but strongly influence the lasing by changing the electron and excited state densities and kinetic temperatures.

- Although fission fragment pumping behaves like electron beam pumping for laser excitation, W values (energy expended per ionization or excitation reaction) for gas mixtures are not easily scalable from the pure gas values (Ohw89).
- The gas temperture and flow have spatial dependences which can only be coupled into the chemical kinetics through elaborate extensions of fluid dynamics computer codes which are not normally written to encompass chemical kinetics (Neu90, Mon91). Radiation transport of resonance and laser wavelengths could also be important in this spatially-dependent model. Because the laser kinetics have not been modeled for steady state pumping with gas flow, it is unknown whether the laser gain will be sustainable in that regime (Hay86).
- Many important atomic parameters (stimulated emission cross sections, spontaneous emission probabilities, etc.) are poorly known.

The University of Illinois has produced valuable chemical kinetics modeling of lasers amenable to reactor pumping (Ohw89), but the uncertainties listed above preclude a more complete understanding of the behavior of RPL's.

In addition to the chemical kinetics, there are neutron kinetics issues related to RPL's. The reactor neutron kinetics are strongly affected simply by inserting the laser package in the reactor (Min87). Since power scales with volume in RPL's, these perturbations will be more severe for high power RPL's. Analysis of these issues is complicated by geometry restrictions dictated by reactor configurations, charged particle transport and energy deposition of the nuclear pump source, and the lasant gas flow.

2.5.3 Maturity

The relative immaturity of RPL experiments and technology leads to several problems when considering these lasers for power beaming systems. RPL experiments have only recently moved out of the proof-of-principle stage and have yet to be run at steady state with thermal reactors or scaled to the high powers required for power beaming. Their fluid dynamics, neutron kinetics, and chemical kinetics must be better understood before they can be optimized for efficiency or power output. There are many aspects of RPL engineering that are still being explored in the laboratory and will affect the suitability of this technology for power beaming.

This immaturity results in a lack of data which is needed for an adequate system analysis. Systems studies require cost, lifetime, mass, safety, consumables, efficiency, reliability, maintainability, and availability data which must be generated over a significant number of RPL runs. These classified experiments are expensive and are not performed frequently enough to yield reliable systems analysis data.

As RPL technology progresses, the power beaming community will continue to develop its system architectures based on more mature technologies such as solid-state lasers and receivers. These subsystems must be closely integrated to ensure an acceptable system efficiency. Unless RPL technology can advance quickly, it will likely be absent from proposed power beaming system studies in the foreseeable future because it will not be easily coordinated with the more established receiver systems.

The current plans for the SNL/INEL experimental effort call for a technology demonstration in the near future which will focus on kinetics, laser extraction, and beam quality. Volume scaling experiments will follow within three to five years and an engineering demonstration is planned within a decade.

2.6 Summary

Reactor-pumped lasers are not suitable at this point for consideration as part of a power beaming system. They are still an experimental technology whose principles have not been developed to the point where accurate data can be found or projected for the proper system studies. They are capable of generating the laser wavelengths required by the power beaming community, but cannot currently compete with more established solid state lasers and receivers with regard to the many laser design criteria listed in Table 2. Given the relative paces of research in solid state physics and reactor-pumped lasers, this situation is not likely to change in the near future.

2.7 Further Reading

Jalufka's report (Jal83) contains a good overview of RPL concepts and a review focusing on NASA efforts in the 1970's. G.H. Miley has produced a number of reviews (Mil77, Mil84, Mil89b) of RPL's. For an interesting historical perspective on RPL's, an early review is given by Thom (Tho72). Prelas (Pre88) has good review of nuclear-driven flashlamps. For information on power beaming, the PNL 1991 Power Beaming Workshop bulletin (PNL91) and the PNL Space Power Generation and Distribution Program Documents (PNL90) are good sources.

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