A Review of Nuclear Pumped Lasers and Applications (Asteroid Deflection)

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A Review of Nuclear-Pumped Lasers and Applications (Asteroid Deflection)

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Abstract

A graduate course focused on bringing cutting edge research into the classroom, titled Nuclear Pumped Lasers and applications, was taught at the University of Missouri in 1991 as a topics course; due to renewed interests in high power/high energy lasers for civilian applications, the course has been updated with new research and is being offered in the spring of 2014. Nuclear-Pumped Laser (NPL) technology was a part of the strategic defense initiative (SDI) program in the 1980's. NPLs have since faded from the United States research agenda but they remain an active part of the research agenda in other countries, notably in Russia and other nations in the former Soviet Union as well as China [1] which has a cooperative agreement with Russia [2]. The reason for this broad interest in the technology is that a NPL can scale to high power/energy levels (potentially up to 100 MW Continuous Wave (CW) beam power). Military applications have historically dominated the NPL research agenda. However, there are significant humanitarian applications for high power/energy lasers. For example a high power CW NPL would have the capability to deflect asteroids or comets. Other important applications are in space propulsion, power transmission, and asteroid mining. Despite the promise, there are significant problems in NPL development [3, 4]. High power/high energy gas lasers by their nature require high pumping power densities (defined as the Watts/cm^3 deposited in the laser medium). That is why many of the most powerful gas lasers are pulsed. Nuclear-pumping does not generate high power densities as compared to electrical pumping, but it does generate high energy densities. This limits the type of high power/high energy gas laser systems that can be driven by NPL technologies. Other issues involve the size and scale of NPLs using gas laser technology as well as the design of reactor cores dedicated to the production of laser beams. Several promising approaches were developed including the development of nuclear-driven flashlamps [5] which can increase the effective pumping power density through photon focusing and thus open up new possibilities for both gaseous and solid-state high power/high energy laser systems.

1.   Introduction

1.1.   Summary of NPL Research

NPLs have been under investigation since 1963 when first proposed by L. Herwig [3-5]. The fundamentals of nuclear-pumping are that the ions produced from nuclear reactions are used directly as the driver for the excitation of the laser medium. High power, high efficiency lasers with short wavelengths (less than 1000 nm) typically require high pumping power densities (greater than 100 kW/cm^3) [6]. Nuclear-pumping methods are able to achieve high energy density (up to 46 J/cm^3) but the pulse width of the energy delivery system is limited to the pulse width of the reactors that deliver the neutrons for the reactions (Table 1). Thus a fast burst reactor which has the shortest pulse width is limited to a power density of 46 kW/cm^3 or so. In contrast, an electron beam can deliver its energy in a pulse width of a microsecond or so thus

achieving power densities on the order of 1 MW/cm^3. Hence NPLs must be based on specialized high power/high efficiency lasers which can operate at moderate power densities or use a technique called energy focusing to enlarge the base of useable lasers.

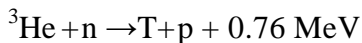Table 1. Parameters of reactors that are typically available in research today.

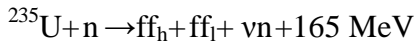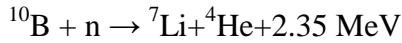| Reactor Type	Peak Neutron Flux Neutrons/cm^2-s	Full Width Half Maximum (ms)	Reference
Fast Burst	1x10^{19} fast neutrons 1x10^{17} thermal neutrons	0.2	[6, 7]
TRIGA	2x10^{16} fast neutrons 2x10^{16} thermal neutrons	10	[6]
Steady-State Research Reactor	4x10^{14} fast neutrons 5x10^{14} thermal neutrons	∞	[6]

Table 2. Comparison of the absolute efficiency for the nuclear pumping source.

Pump Source	A Charged Particle Energy Produced (MeV)	B Charged Particle Energy Available (MeV) (a)	C Nuclear Energy Produced by the Source Reaction (MeV)	D Addition Energy to Produce Neutron (MeV)	Pump Source Efficiency η_{NP}=B/(C+D)
^{10}B Coating	2.35	0.5	2.35	400 (b)	0.001
^{3}He Gas	0.76	0.76	0.76	400 (b)	0.002
^{235}U Coating	165	40	200	None (c)	0.20
^{235}U Dust	165	120	200	None (c)	0.6
^{235}UF$_6$ Gas	165	165	200	None (c)	0.8
Uranofulleren	165	165	200	None (c)	0.8

(a) Only 50% of the charged particles go in the right direction from a coating and self absorption in the coating must be considered. An aerosol fuel particle can lose about 27% of its energy through self absorption. A gaseous form of UF$_6$ or uranofullerens have minimal self absorption.

(b) ^{3}He and ^{10}B reactions must be initiated by neutrons produced by an external fission reactor. About two fissions releasing ~400 MeV are required to produce one neutron captured by the ^{3}He or ^{10}B reactions.

(c) ^{235}U pumping sources can be self critical so there is no energy expenditure to create a neutron for the reaction.

NPLs have utilized the following neutron-initiated nuclear reactions to produce charged particles,

$$^3\text{He} + n \rightarrow T + p + 0.76 \text{ MeV}$$

$$^{10}\text{B} + \text{n} \rightarrow \,^{7}\text{Li} + \,^{4}\text{He} + 2.35 \text{ MeV}$$

$$^{235}\text{U} + \text{n} \rightarrow \text{ff}_h + \text{ff}_l + \nu\text{n} + 165 \text{ MeV}$$

where the 165 MeV is the charged particle recoil energy (not total energy produced in fission), ff_l is the light fission fragment, ff_h is the heavy fission fragment, and ν is the statistical average number of neutrons released per fission.

Of these charged particle sources, only fission promises high enough efficiencies for applications (see Table 2). As is shown in Figure 1, the uranium can be present in the system as: a) a surface source, or b) a volume source.

A. Coated tube design
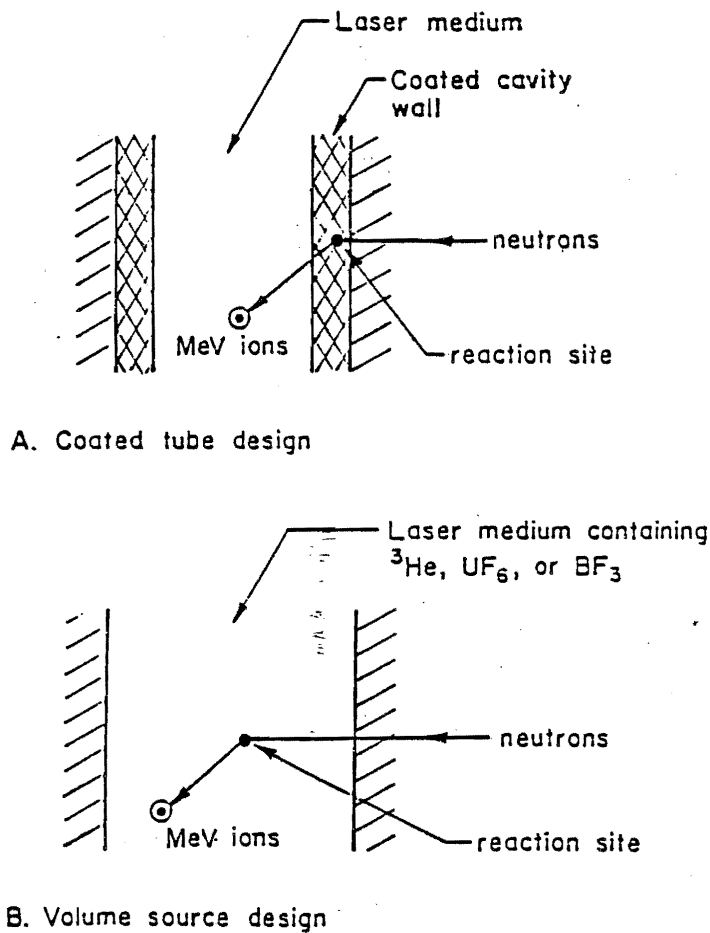

B. Volume source design

Figure 1. Nuclear-pumping sources are of two forms: A) a surface source where the high energy ions are created in a coating on the walls of the cell or B) a volume source where a gas or aerosol fuel is used to create the high energy ions in laser medium [6].

Surface sources have low efficiency since nuclear reactions are isotropic. (50% of the ions are emitted in the wrong direction and are immediately absorbed by the wall. Of the remaining 50%, less than half of the ion energy will eventually escape the coatings.) Therefore

surface sources, although they have the advantage of being chemically inert, have low efficiencies (less than 20%) and can only be scaled to volumes on the order of the ion range in the gas. Several designs of reactors using a surface source interfaced with the reactant have been published for lasers and chemical processing, however, in addition to the transport inefficiency, this technique also contaminates any reactant which comes in direct contact with the fuel [5, 6]. Surface sources could be used in an energy focus application [8] because the source material can be coated by a reflecting surface. This point will be discussed in section 2.

Volume sources can produce a much a greater energy release because half the charged particle energy is not lost in a wall and the volume is not constrained to the charged particle range. Until 1981, UF_6 was the only available volume fission source. UF_6 vapor however produces strong quenching of the chemical kinetics of most systems [3-6] and cannot be used for most fluorescence production applications because of its very high absorption at wavelengths shorter than 420 nm (Figure 2). An aerosol core reactor provides a volume source without the major drawbacks of UF_6 [9-11]. Calculations by Chung and Prelas suggest that 50 to 80% of the energy generated in a micropellet will be available to pump the fluorescer (See Figure 3) [12]. Another major advantage of the aerosol concept, in addition to the efficiency, is that the essentially inert micropellets will not affect the chemical kinetics of the reactant being "pumped". Finally, the aerosol concept can be used with materials such as silicon carbide which should allow high operating temperatures. This last advantage implies that other energy producing cycles can be added to make the system even more efficient [5]. A gaseous core-like reactor concept using uranofullerene (a uranium 235 atom trapped in a C60 cage) as a fuel has also been suggested [13]. A reactor fueled with uranofullerenes should be chemically inert, and would interface well with laser media or flashlamp media.

Table 3. Maximum power deposition from various sources (W/cm^3) with a gas laser [5, 6].

|	Source Type	Fast Burst Reactor	Pulsed TRIGA Reactor	Steady State Reactor	Radionuclides		
					Po210	Ra228	Rn222
Surface	^{10}B	106	26.5	1.06			
	^{235}U	4,740	119.0	4.74			
	Radionuclide				0.042	0.263	
Volume	^{3}He gas	14,820	371.0	14.80			
	^{10}BF$_3$ gas	3,500	87.4	3.50			
	^{235}UF$_6$ gas or Uranofullerenes	44,300	1,100.0	44.30			
	Radionuclide						5.05
Aerosol	^{235}U Non-Reflective	22,000	546.3	22.0			
	^{235}U Reflective	46,000	1,142.0	46.0			
	Radionuclide Non-Reflective				0.1953	1.222	
	Radionuclide Reflective				0.408	2.221	
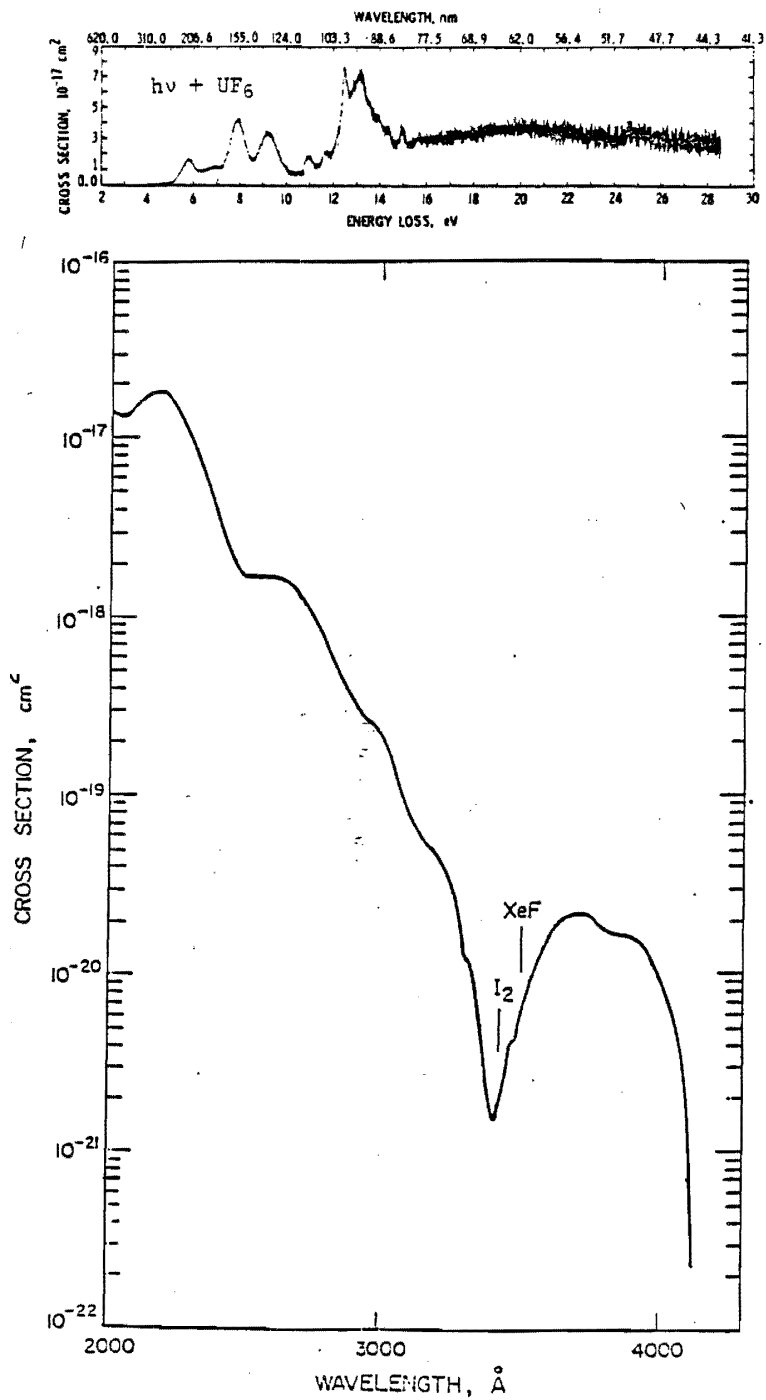
Figure 2. UF$_6$ photoabsorption spectrum [4].
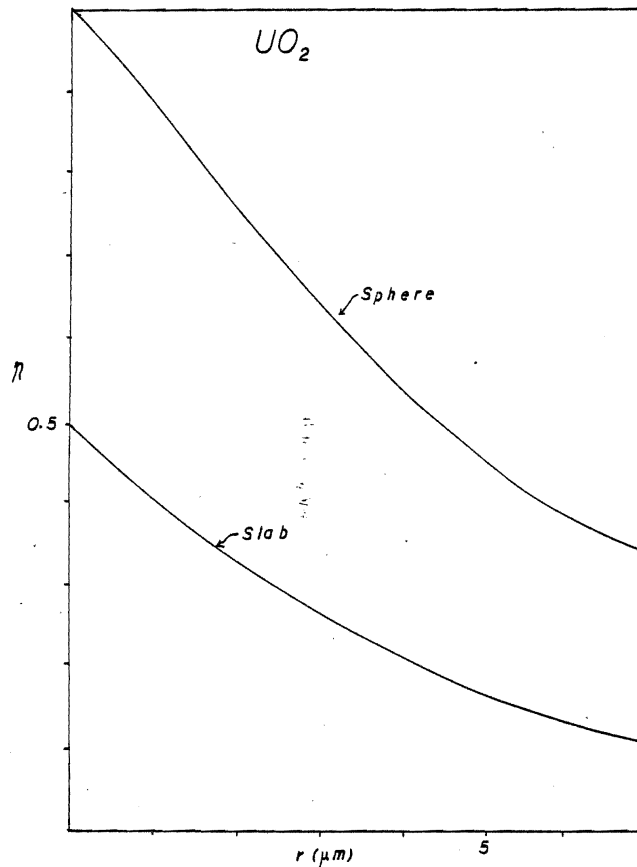
Figure 3. Fission fragment transport efficiency in microspheres and slabs of various thicknesses [12].

1.2. High Power/High Energy Lasers

As previously discussed the key to driving a laser is in the achievement of the minimum threshold power density. It has been said that with enough power density, it is possible to make a laser from virtually any material-even jello. To make a useful nuclear-pumped laser, the power density should be low to moderate (Watt/cm^3 to Kilowatts/cm^3) and the laser should be relatively efficient (> 1%). Wavelength is also a consideration for a high power/energy laser because of the physics of diffraction limited optics which governs its size and focal length. To understand the importance of diffraction limited optics, consider the angular spread of the laser beam,

$$\Delta\theta \approx \lambda/d \qquad\qquad\qquad (1)$$

where, $\Delta\theta$ is the angular spread, λ is wavelength is meters and d is the diameter of the optics.

The angular spread of the beam determines the range of the focused laser beam before its intensity disperses. As an example, assume that a xenon fluoride laser with a wavelength of 351 nm is tasked to deflect a 4000 meter radius asteroid at a distance of 400 billion meters from earth. The first step is to diagram the problem as shown in Figure 4. Due to the angular spread of

a laser beam, one diagrams the beam from its optical aperture to the asteroid (Figure 4). The figure shows an earth based laser hitting a 4000 m radius asteroid in the asteroid belt which is 400 billion meters away. A laser beam must have enough intensity to ablate the surface of an asteroid or comet. An intensity of 10 MW/m^2 or greater is necessary to evaporate stone or icy surfaces [14]. In reference 14, the situation of applying a steady thrust on the asteroid was discussed. The change in velocity necessary to deflect an object by the radius of the Earth is:

$$v \approx 0.01 \frac{m}{s} \qquad (2)$$

The resulting thrust which is imparted on an asteroid by steadily ablating the surface with a high intensity beam of photons is ~3.3 x 10^{-5} N W^{-1}. Using the model introduced by Melosh, et. al. [14] for deflecting an asteroid using photons, an equation can be derived showing the relationship between laser power, asteroid diameter and irradiation time needed to deflect the orbit of an asteroid or comet at least one earth diameter to prevent an earth strike. The force generated by the evaporation of mass is (see equation 3).

$$F = 0.5 \frac{dm}{dt} v_e \qquad (3)$$

where $\frac{dm}{dt}$ is the mass ejection rate and v_e is the velocity of the ejected material.

The heat of evaporation for a silicate asteroid is 15 MJ/kg and the velocity of the atoms being ablated (v_e) is about 1000 m/s. Setting the mass ejection rate equal to the laser power (L_p, Watts) divided by the heat of evaporation, equation 3 can be rewritten,

$$m_a a_a \approx 0.5 \frac{L_p(W)}{15x10^6 (J/kg)} 1000(\frac{m}{s}) \qquad (4)$$

where m_a is the mass of the asteroid in kg, and a_a is the acceleration of the asteroid.

The mass of a silicate asteroid is its density (3900 kg/m^3) times its volume ($\frac{4}{3}\pi \frac{(d_a)^3}{8}$), where d_a is the asteroid diameter in meters. Equation 4 can now be solved for L_p.

$$L_p \approx 3.333x10^{-5} m_a a_a \qquad (5)$$

Using $m_a = 3900 (\frac{kg}{m^3}) \frac{4}{3}\pi \frac{(d_a)^3}{8}$, $a_a = \frac{\Delta v}{\Delta t}$ and calling Δv the velocity change required to deflect an asteroid one earth radius (a velocity change of about 0.01 m/s) [14], an equation for laser power as a function of asteroid diameter and irradiation time, t (where Δt=irradiation time t) can be found,

$$L_p = 6.125x10^5 \frac{(d_a)^3}{t} \qquad (6)$$

where d_a is asteroid diameter in m, t is irradiation time in s; L_p is laser power in watts.
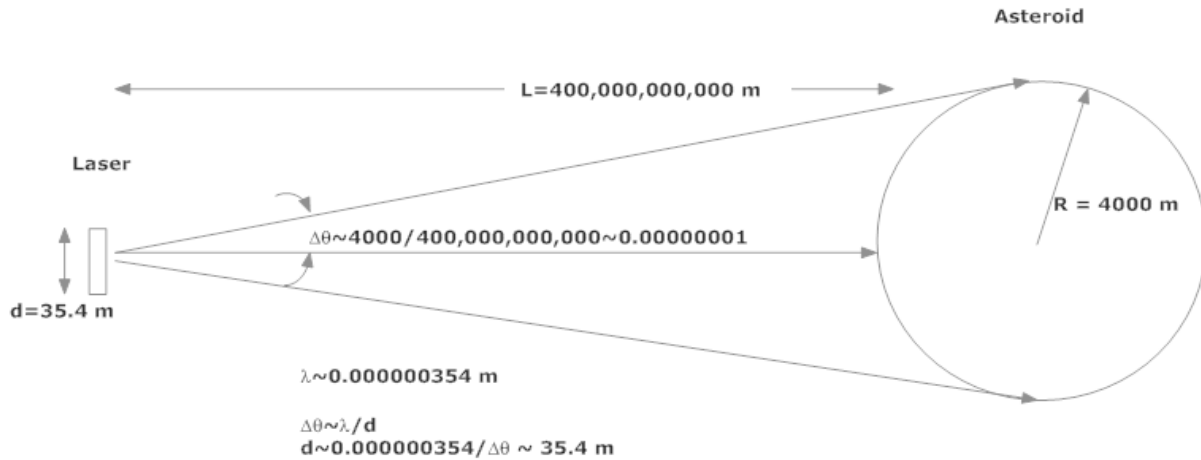
Figure 4. Illustration of a laser in an earth orbit irradiating an asteroid.
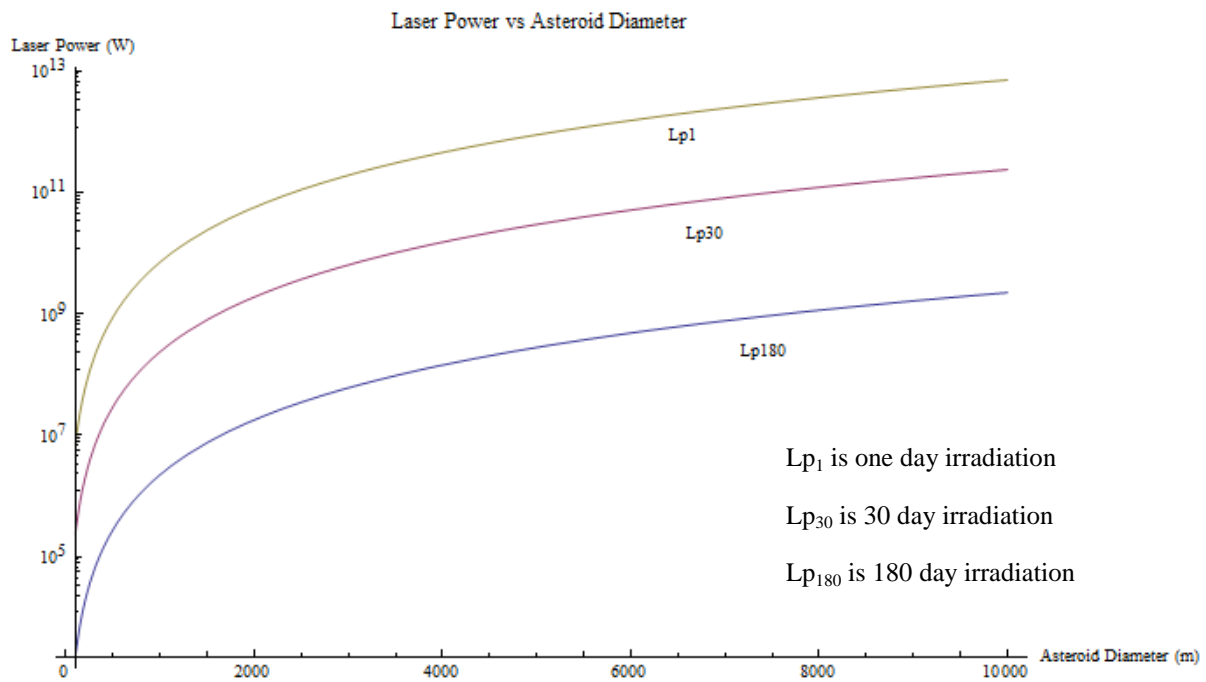

Figure 5. Laser power vs. asteroid diameter for various irradiation times.

The laser power required to deflect asteroids of various diameters is shown in Figure 5 for various irradiation times. For smaller asteroids (~ 500 meter), the laser power and irradiation times are moderate (30 days and < 51 MW). However, for very large asteroids (~ 10,000 meters) the power and irradiation time is significant (365 days and >17 GW).

Something in common for all high power/energy laser applications is a requirement on the beam intensity on the target (e.g., asteroids needing > 10 MW/m^2 to evaporate the surface).

An analysis similar to that of asteroid deflection can be done for Ballistic Missile Defense (BMD). BMD applications, like asteroid deflection, have certain beam intensity and irradiation time requirements. The energy per unit area (J/m^2) is called the fluence (F). Each mission has a fluence and total energy requirement on target in order to achieve a goal; e.g., deflection of an asteroid or destruction of a ballistic missile. The fluence is calculated from the laser power, L_p (W), the irradiation time, t (s), the area of the spot size on target, A (m^2), and the laser beam transmission efficiency from the laser aperture to target (where beam energy can be lost transmitting through air for example), T (see Equation 7) [15].

$$F = \frac{T \, L_p t}{A} \tag{7}$$

The spot size is a function of the far field divergence angle, $\Delta\theta$, the distance to the target, R, the laser wavelength, λ, and the diameter of the laser optics, d (see Equation 8).

$$\Delta\theta \cong \frac{\lambda}{d} \tag{8}$$

The spot size is,

$$A = \frac{\pi R^2 \lambda^2}{d^2} \tag{9}$$

So assuming T=1,

$$F = \frac{L_p t d^2}{\pi R^2 \lambda^2} \tag{10}$$

The laser power must be delivered to the asteroid in a beam with an intensity of at least 10 MW/m^2 in order to evaporate the surface and create thrust. For example, assume that the asteroid is 1.4 km in diameter. Looking at Figure 5 for a 180 day irradiation, the laser power should be at least 108 MW CW. Given these assumptions, the distance of the laser from the asteroid can be calculated by dividing the power of the laser by A and setting that quantity equal to 10 MW/m^2.

$$10 \text{ MW/m}^2 = 108 \text{ MW/A} \tag{11}$$

Equation 9 for "A" is substituted into equation 11 and the resulting equation is rearranged to find the following relationship for R,

$$R = (10.8 \ d^2 / \pi\lambda^2 \ )^{1/2} \tag{12}$$

The importance of wavelength can be demonstrated through diffraction limited optics by seeing how two different lasers compare: a CO_2 laser with a wavelength of 10.6 micrometer and a XeF laser with a wavelength of 351 nanometer. The required distance between the laser (R_{CO_2} for CO_2

and R_{XeF} for XeF) and the asteroid is calculated using equation 12 and the results are shown in Equation 13 for laser aperture diameters of 1 meter and 10 meters,

$$R_{CO_2} = \begin{cases} 175 \; km \; for \; d = 1 \; m \\ 553 \; km \; for \; d = 10 \; m \end{cases}$$

$$\hspace{8cm} (13)$$

$$R_{XeF} = \begin{cases} 167{,}000 \; km \; for \; d = 1 \; m \\ 528{,}000 \; km \; for \; d = 10 \; m \end{cases}$$

Thus, a CO_2 laser must be much closer to the asteroid than the XeF laser in order to meet the 10 MW/m^2 criterion needed to ablate the surface.

In the example of the deflection of a 1.4 km diameter asteroid, the product of laser power and irradiation time, L_pt, must be greater than or equal to 1.68×10^{15} J and is related to the total momentum change generated by the evaporating mass from the asteroid surface. The laser must operate continuously for 180 days at a power level of 108 MW in order to accumulate enough energy to evaporate enough mass from the asteroid in order to deflect it. In contrast, for a ballistic missile defense system, the L_pt product must be on the order of 10^5 J (for a hardened target) to shoot down a ballistic missile [15]. The 10^5 J on target for BMD is feasible with a very large pulsed laser. However, the 1.68×10^{15} J needed for asteroid deflection can only be delivered by a very large CW laser over long irradiation times. The challenge of building a high power laser for the BMD mission or the high energy CW laser needed for asteroid deflection both fit very well with the strengths of NPL technology.

1.3. Nuclear Pumped Lasers

One of the main problems with power sources for space based lasers is the energy stored by the fuel (which directly influences the mass of the laser system). In Table 4, the energy stored in 1 kg of various fuel sources is shown. Hydrogen has one of the highest specific energies available in a chemical energy storage system and is used here as an illustration of the maximum expected specific energy for chemical energy storage. The energy stored in the fuel is an important factor for a deep space mission. In order to generate the 1.68×10^{15} J needed for the deflection of a 1.4 km diameter asteroid, it would require at minimum, for a 100% efficient energy conversion system, 1.87×10^{-2} kg of antimatter, 2.92 kg of DT, 1.17×10^{1} kg of U-235, 7.63×10^{2} kg of Pu-238 or 1.17×10^{7} kg of hydrogen (Table 5). However, converting energy from a fuel to laser beam energy is not even close to 100% efficient. Consider the case of an electrically pumped laser using a fuel cell powered by hydrogen and oxygen. The best case for fuel cell efficiency is about 50%. The power transmission and conditioning circuits are about 80% efficient. The efficiency of an e-beam driven XeF laser is about 1%. Thus the minimum mass for the hydrogen fuel needed for this mission is about 2.3×10^{9} kg (i.e., Fuel Mass=1.17×10^{7}kg/(0.5*0.8*0.01)=2.3×10^{9} kg) If the mass of the fuel cell, the mass of the power circuits, the mass of the laser, the mass of the radiator, the mass of the optics and the mass of the laser gas were also included, the total mass of the system would be significantly larger. In contrast, the amount of U-235 needed to supply the energy is so small, that it not nearly enough mass to make up the fuel for a critical nuclear reactor. The minimum mass of fuel for a critical nuclear reactor/laser system is about 100 kg. However, the fuel load in a nuclear reactor/laser system can be designed for more than enough stored energy to deflect a 1.4 km asteroid (or

larger) using a direct nuclear pumped laser with an efficiency on the order of 1% (considering all factors of energy transport from the fuel to the laser medium). The other contributions to system mass are the laser cavity, the laser medium, the reactor control system, the radiator (for heat transfer to space) and the optics. A nuclear-pumped laser system will be a much less massive system than a chemical laser system. This point is made to illustrate that systems based on nuclear fuels will have far less mass than chemical fuels and thus have a distinct advantage for space based systems.

Table 4. Energy storage capability for various fuels. (note that hydrogen is representative of chemical energy sources.)

Storage type	Specific energy (MJ/kg)
Antimatter	89,900,000,000
Deuterium-tritium fusion	576,000,000
Uranium-235	144,000,000
Pu-238 α-decay	2,200,000
Hydrogen	143

Table 5. The total energy needed to deflect an asteroid of a given diameter and the minimum mass of U-235 or hydrogen needed to store that amount of energy.

Laser power (W)	Asteroid Diameter (km)	Lp*t (J) (t=180 day)	Mass U235 (kg)	Mass H_2 (kg)
3.94E+04	0.1	6.13E+11	4.25E-03	4.28E+03
4.92E+06	0.5	7.66E+13	5.32E-01	5.35E+05
3.94E+07	1	6.13E+14	4.25E+00	4.28E+06
3.15E+08	2	4.90E+15	3.40E+01	3.43E+07
1.06E+09	3	1.65E+16	1.15E+02	1.16E+08
2.52E+09	4	3.92E+16	2.72E+02	2.74E+08
4.92E+09	5	7.66E+16	5.32E+02	5.35E+08
8.51E+09	6	1.32E+17	9.19E+02	9.25E+08
1.35E+10	7	2.10E+17	1.46E+03	1.47E+09
2.02E+10	8	3.14E+17	2.18E+03	2.19E+09
2.87E+10	9	4.47E+17	3.10E+03	3.12E+09
3.94E+10	10	6.13E+17	4.25E+03	4.28E+09

Estimating the mass of a NPL system is complex because of the efficiencies that govern the conversion of the energy stored in the nuclear fuel into laser power. The choice of the laser is important both for the laser efficiency as well as the wavelength. Due to the limited power density that is available from nuclear-pumped drivers, it took 11 years for the first NPL to be demonstrated from the time that they were proposed in 1963 to the time that gamma rays from a thermonuclear explosion were used to pump a xenon excimer laser and a hydrogen fluoride laser (Table 6). Soon afterwards the CO NPL was reported which used a fast burst nuclear reactor as the pump source, thus representing the first NPL that used a nuclear reactor. About 50 NPLs have been discovered to date (Table 6). The main characteristic of these NPLs are that they have low threshold pumping power densities. The highest efficiencies achieved thus far are between 1 and 2% (it should be noted that advanced NPL concepts, to be discussed later, can potentially achieve efficiencies on the order of 10 to 60%). All of the NPLs found thus far, with the exception of one solid-state laser, were gas lasers. Gas lasers have notable advantages. For one, they are not susceptible to radiation damage. However, they also have disadvantages. Due to low atomic densities of a gaseous medium, a gas laser will have relatively large volume thus leading to systems which have a size and volume (greater than 5 m^3) that may require assembly in space through the launch of multiple modular components [10]. On the other hand, solid-state systems can be susceptible to radiation damage but can have a relatively small volume (less than 1 m^3) which can be launched as a single payload [16].

Table 6. Summary of NPLs that have been discovered to date.

Laser [gas mixture]	Wavelength (nm)	Group	Pumping Source	Threshold power density (W/cc)	Efficiency %
Xe excimer [17]	170	LLNL	Gamma rays from a thermonuclear explosion	~$1x10^6$	unknown
HF [18]	2500 to 3000	LANL	Gamma rays from a thermonuclear explosion	~$1x10^6$	unknown
CO [19] [He+N_2+CO]	5100 to 5600	Sandia	Fission Products from U-235 film	$1.86x10^3$	1
Xe [20] [He + Xe]	3500	LANL	Fission Products from U-235 film	1.9	$2x10^{-5}$
N [21] [Ne+N_2]	860, 939	U of I	Products from B^{10} film	4.5	$5x10^{-5}$
Hg^+ [22]	615	U of I	Products from B^{10} film	4.5	$9x10^{-5}$
Ar [23]	1790, 1270	NASA	Products from	$9.8x10^2$	$1.0x10^{-3}$

			He3 gas		
Xe [24] [He + Xe]	2026, 3508, 3652	NASA	Products from He3 gas	1.6×10^2	1.57×10^{-2}
Kr [25] [He+Kr]	2520, 2190	NASA	Products from He3 gas	5.2×10^2	4×10^{-5}
Cl [25] [He + Cl_2]	1586	NASA	Products from He3 gas	1.1×10^2	2×10^{-4}
C [26] [He+CO or CO_2] [Ne+ CO or CO_2] [Ar+CO_2]	1450	U of I	Products from B^{10} film	0.04	6×10^{-3}
Ar [27] [He+Ar]	2397, 1190, 1150	USSR	Products from U-235 film	3.7×10^2	2×10^{-2}
Xe [27] [He+Xe]	2630, 2480	USSR	Products from U-235 film	3.7×10^1	1.33
Cd [28] [He+Cd]	534, 538	USSR	Products from He3 gas	3.11	8×10^{-3}
CO_2 [29] [N_2 transfer to CO_2 + He]	10600	UF	Products from B10 Film	2.7×10^1	1
Xe [30, 31] [He+Ar+Xe] [Ar+Xe]	1730, 2030	Sandia	Products from U-235 film	~10	2
Nd^{3+} with the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition in NdYag [16] [Pumped with a Xe and Kr flash lamp]	1060	U of Missouri	Products from Products from He3 gas	0.0005	~1
Ne [32] [He+Ne+H}	585.3	U of I	Products from He3 gas	0.001	0.1
I [33] [XeBr flashlamp Pumped C_3F_7I].	1310	U of I	Products from He3 gas	~0.4	0.6

It is desirable to design an efficient short wavelength NPL that operates at a steady-state high power level. The key to such a design is a system that is able to provide a high enough pumping-power density to the laser while the reactor is in steady-state operation. This is a difficult task given that efficient short wavelength lasers typically require high pumping-power densities (>10 kW/cc) while reactor fuel typically operates at a lower pumping-power density

(<5 kW/cc). This is the reason that so few nuclear-pumped lasers have been discovered (about 50 or so) to date. The lasers in Table 6 are some of the few that can operate at relatively low power densities.

A method to boost the pumping power density of an NPL was developed in 1980 [34, 35] called the energy focus. The elements of the energy focus are that a nuclear-driven fluorescer produce photons from spontaneous emission and a non imaging concentrator is used to focus the photons into the laser medium (Figure 4). The energy focus reflects the photons from a large volume lamp to a small volume absorber (laser medium) [8, 10, 11, 36]. In Figure 4, a simplified design is shown for a simple box lamp/reflector of length L and the absorber has a thickness of a few photon mean free paths (δ). The power density in the laser will be much greater than the power density in the lamp (Equation 14).

$$P_{laser} = P_{lamp}\eta_f\eta_{tr}\frac{L}{\delta} \qquad (14)$$

where P_{laser} is power density of the laser, P_{lamp} is power density in the lamp, η_f is the fluorescence efficiency and η_{tr} is the photon transport efficiency.

If the reflector were perfect with no photon transport losses, then using η_f of 0.5, η_{tr} of 1, L of 10 m, δ of 10×10^{-6} m (for a solid-state material), and P_{lamp} of 40 W/cm^3 (for a steady-state reactor), it is found that,

$$P_{laser} = 40 x 0.5 x \frac{10}{1x10^{-5}} = 2x10^7 \ W/cm^3 \qquad (15)$$

Reflector materials are not perfect but a right cylinder using a metallic reflector (e.g., aluminum for the UV-Visible, Sliver for the Visible) makes a reasonably good waveguide. Its transport efficiency (η_{tr}) is on the order of 60% for a long box [37]. With 60% transport efficiency, the power density in the laser is about 12 MW/cc. This power density would be sufficient to drive most photolytic lasers.
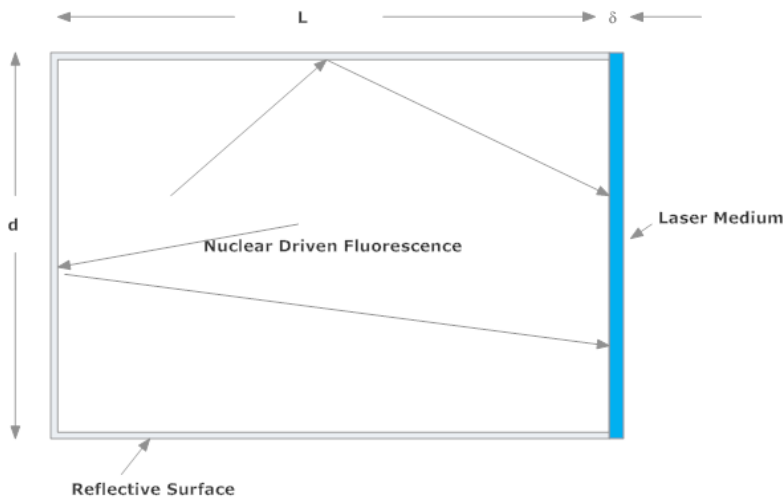

Figure 4. An illustration of the principle of the energy focus concept [34]. (Note that L is length of the nuclear driven fluorescence chamber, d is its diameter and δ is the thickness of the photolytic laser medium.)

The energy focus is an advanced NPL concept that can be used to pump high efficiency gas lasers (such as the Iodine laser with a potential efficiency up to 10%) or high efficiency solid-state lasers (such as GaN with a potential efficiency up to 50%).

2.   Nuclear Pumped Laser Systems

Two types of NPL systems have been examined; solid-state NPL and gas NPL. Each has advantages and disadvantages. Photolytically driven solid-state laser media have low threshold power densities as seen in Table 7. Plus, the use of the energy focus enhances the capability of the solid-state nuclear-pumped laser. Designs of nuclear-pumped solid-state laser systems show promise [16, 38, 39]. It is also possible to use a direct drive nuclear-pumped solid-state laser which will have sufficient power density [40] to meet threshold power density conditions. The principle of a direct-drive solid-state laser takes advantage of the short range of fission fragments to boost the power density to a thin 10 μm layer in the solid-state laser medium.

Gas lasers driven directly by nuclear fission fragments have a limited power density in the laser medium (See Table 3, 4.74 W/cc is the maximum feasible power density for a surface source in a steady-state reactor). A direct-drive system requires that the reactor be pulsed in order to increase the pumping power density (See Table 6, the 2% efficient xenon laser which can only be driven by a surface source has a threshold power density of 10 W/cm^3). Steady-state reactors do not have the power density to drive a CW laser. On the other hand, photolytically driven nuclear-pumped gas lasers can use the energy focus scheme described above to drive a continuous wave laser with a steady-state reactor. They also have some mass reduction advantages when applied to large scale systems. The gas can flow thus helping with thermal management [6, 8, 9, 41]. Gas lasers have also been examined using solar pumping [42] but the size and mass of these systems is much larger than that of NPL systems.

Table 7. The properties of solid-state laser crystals. The operational wavelength(s) (ω_1), stimulated emission cross section (σ_{se}), upper laser lifetime (τ_{ul}), thermal conductivity (k), threshold power density and current size limitations are shown.

| Medium	ω_1 (μm)	σ_{se} (10^{-19} cm^2)	τ_{ul} (μs)	k (W/m-K)	Threshold Power Density (W/cc)	Size (cm)
Nd:Cr:GSGG	1.06	1.3 at 300 K	222	6	115	9.6x19x0.5
Cr:GSGG	0.75 to 1.0	0.1 at 300 K	120	6	1149	9.6x19x0.5
Alexandrite	0.7 to 0.82	0.2 at 450 K	260	23	636	r=1. l=10
Ti:Al$_2$O$_3$	0.72 to 0.92	4.1 at 300 K	3.2	NA	3024	30.5x17x4.5
Emerald	0.73 to 0.81	0.2 at 300 K	200	NA	827	>0.7

Table 8. The properties of select gaseous photolytic lasers.

Laser	Pump Molecule	Pump Wavelength (nm)	Laser Wavelength (nm)	Threshold Power Density (W/cc)
XeF*	XeF_2	160	480	15,000
I	C_3F_7I	282	1315	100
HgBr*	$HgBr_2$	193	502	15,000
HgCl	$HgCl_2$	<190	558	15,000

2.1. Photolytic Nuclear-Pumped Solid-State Lasers

An efficient coupling configuration has been discussed for remote, nuclear-driven, fluorescer-pumped, solid state lasers as shown in the energy flow diagram in Figure 5 [43]. By applying the tapered fluorescer cell and a large diameter-to-length ratio hollow lightpipe, the coupling efficiency can be greater than 90% [39]. Figure 6 shows the configuration of an aerosol reactor with the coupling light pipes for pumping the laser driver. The spectral matching is very important for optically pumped lasers. By considering the wavelength of the excimer emission, the laser crystal has to be chosen properly according to the absorption spectra of laser crystals. The laser efficiency η_L is the product of the ratio of the pumping wavelength to the output wavelength of the laser and the extraction efficiency of the laser cavity. The energy flow diagram in Figure 5 shows how the system efficiency is calculated for the relatively compact nuclear-pumped solid-state laser.
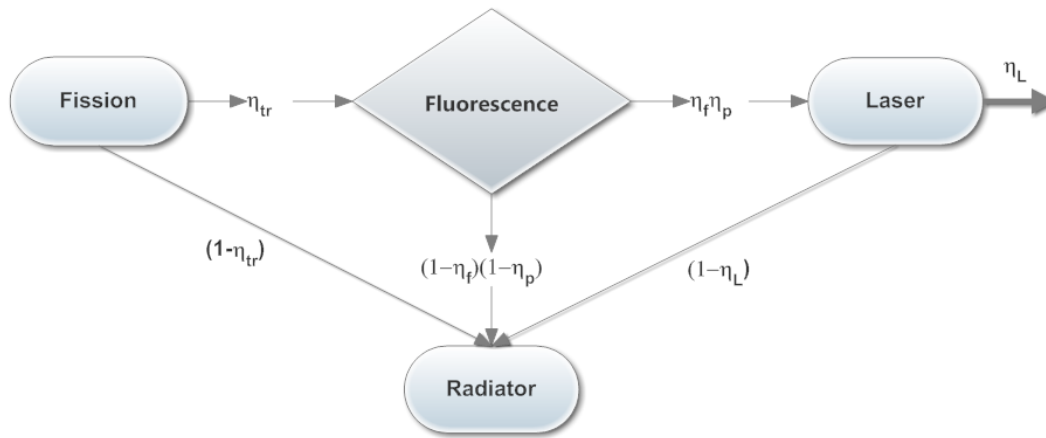
Energy Flow In a Nuclear-Driven Photolytic Laser

$$\eta = \eta_{tr}\eta_f\eta_p\eta_L$$

where, η is system efficiency, η_{tr} is the fission product transport efficiency, η_f is the fluorescence efficiency, η_p is the photon transport efficiency, η_L is the laser efficiency

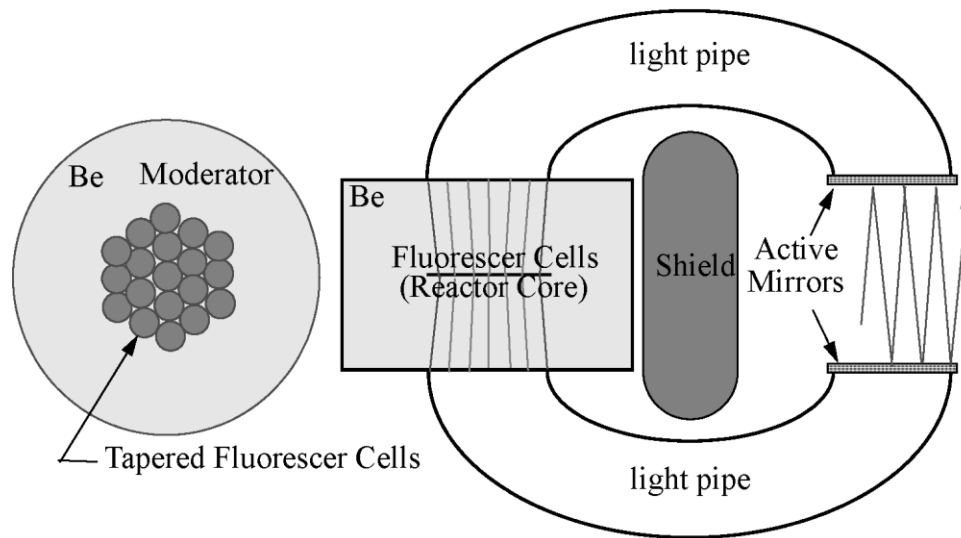Figure 5. The energy flow diagram for a nuclear-driven photolytic laser.

Figure 6. Configuration of an aerosol reactor with coupling light pipes to active mirrors with an expected efficiency of 3% and volume of ~ 1 m^3 [29, 35].

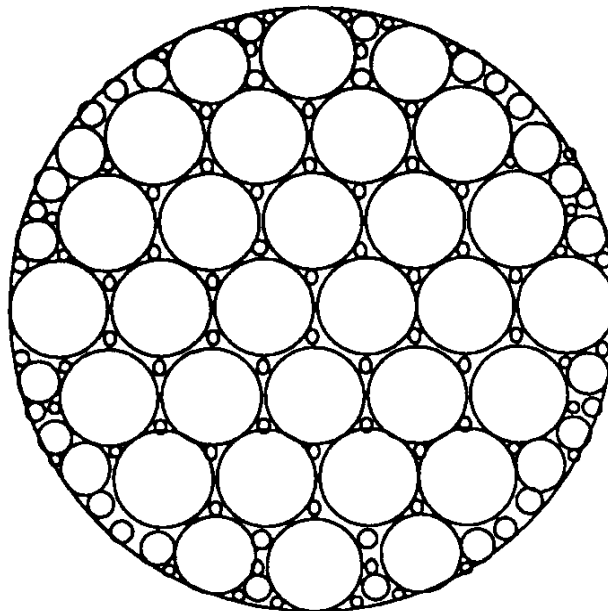Figure 7. Mosaic of active mirror laser amplifiers used in Figure 6 [35].

ARECS REACTOR/LASER

Reflector

LATTICE
CELL

laser
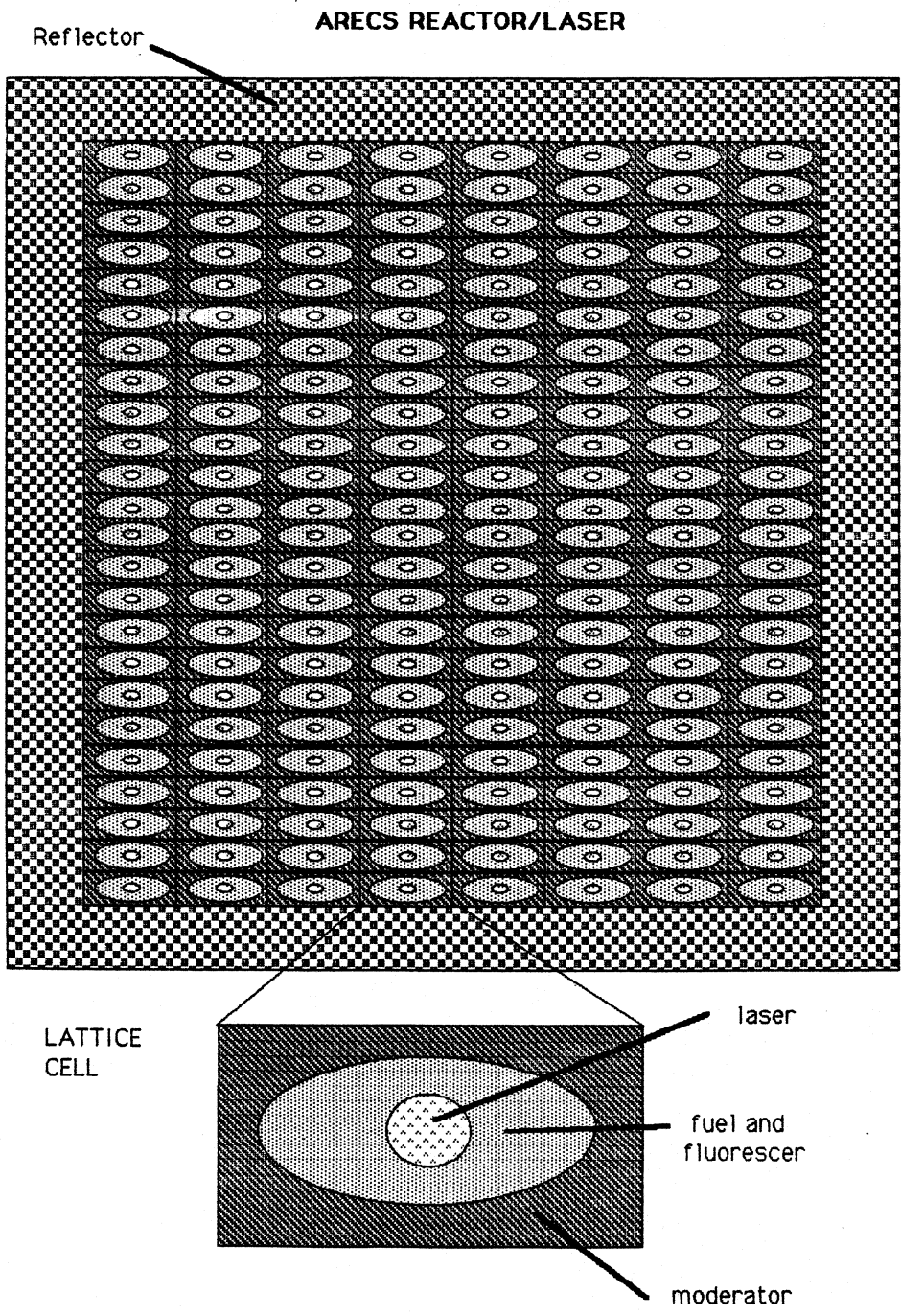
fuel and
fluorescer

moderator

Figure 8. An illustration of a photolytic nuclear pumped iodine laser that is fueled with non-reflective (black) U-235 particles. The mass was estimated to be 15 metric tons and the volume 43 m^3 [24].
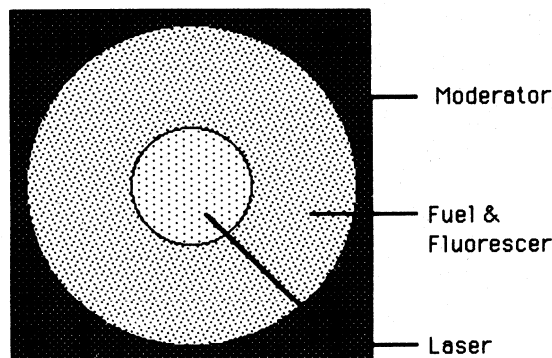
Figure 9. A unit cell of a photolytic iodine nuclear-pumped laser fueled with reflective U-235 particles. The mass of the unit was estimated to be 1 metric ton with a volume of 0.6 m^3 [25].

2.2   Direct Drive Nuclear Pumped Semiconductor Lasers

Semiconductor lasers (such as GaN) can be directly driven by ions from nuclear reactions. Fission fragments have a range of about ~10 μm in the laser medium. A design was developed for a high density reactor core made up of unit cells with a layer of 10 μm 93% enriched U-235, 1 μm diamond and 20 μm semiconductor micro-layers (Fig. 10). The cells are then stacked in a slab design to form the reactor. This stacked cell concept can achieve criticality in a volume of 0.1 m^3 and achieve a CW laser power level of >10 MW. The mass of the reactor and subsystems will be on the order of 2 metric tons.

In this design, the low-Z wide band gap material layer functions as the lasing medium (e.g., SiC, GaN and AlN). It does have some moderating properties. As mentioned previously, these layers must be composed of single-crystal material as the grain boundaries in polycrystalline material would present phasing problems for the laser.

The polycrystalline layers of diamond would function both as a high thermal conductivity material for heat removal and as a moderator. Diamond would be the ideal material for this purpose because of superior properties in radiation hardness, heat conduction and emissivity.

Highly enriched uranium (93% U-235) would be optimum for the fissile layer of this design to maximize the flux to mass ratio of the core for the most compact assembly possible.

This design allows for a reactor small enough to be launched into orbit near an incoming asteroid and power output in the 10 to 100 MW range is sufficient to redirect asteroids as discussed. The payload mass for the laser is within the launch capability of current programs such as the Cassini–Huygens Spacecraft mission to Saturn with a mass of 5,574 kg.
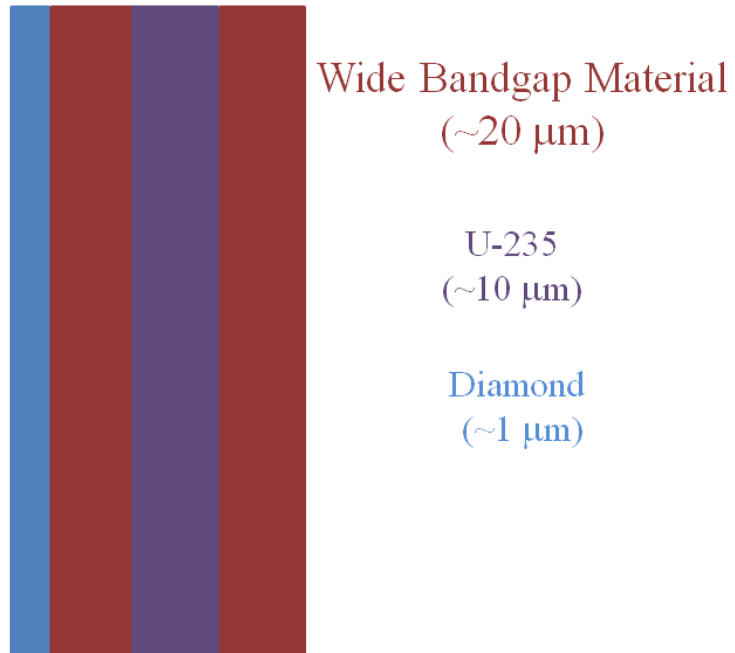
Side View of Stacked Unit Cell in Reactor

Wide Bandgap Material
(~20 μm)

U-235
(~10 μm)

Diamond
(~1 μm)

Fig. 10. Unit cell layout for solid-state nuclear-pumped laser/reactor.

2.3   Direct Drive Nuclear Pumped Gas Laser

A nuclear-pumped laser driven by a surface source is illustrated in Figure 11. A modern high flux nuclear reactor with a surface source is capable of producing a power deposition of 4.74 W/cc (Table 3). A 2% efficient Xe laser requires a threshold power density of 10 W/cc. If a new design for a steady-state reactor is developed which boosts the neutron flux by a factor of 3, it would be possible to direct drive a Xe laser.

Conventional Reactor/NPL (eg 1.3% Xe laser)
with U^{235} Coatings
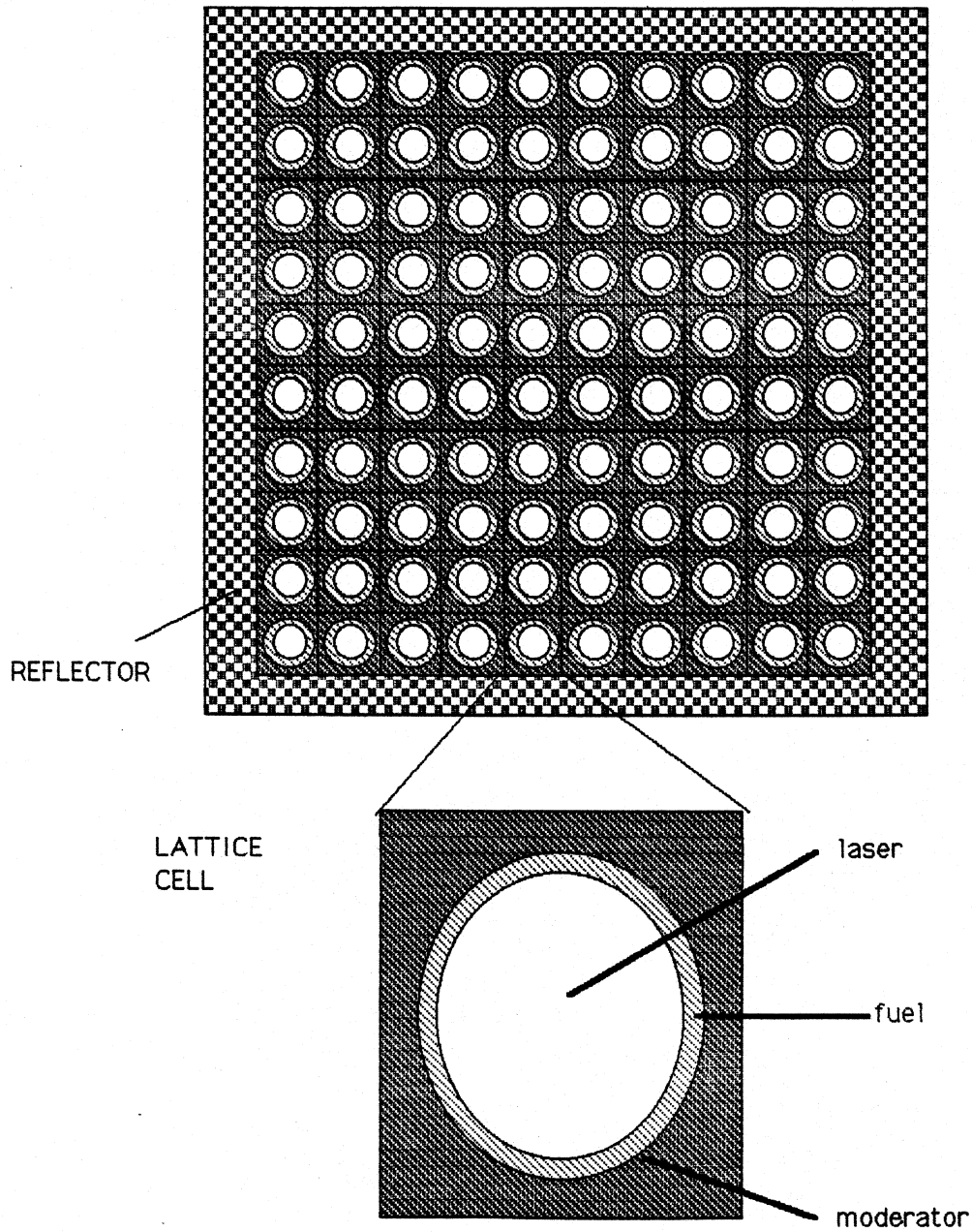

REFLECTOR

LATTICE
CELL

laser

fuel

moderator

Figure 11. An illustration for a conventional NPL/Reactor using a Xe laser. The fuel is a thin coating on the surface (surface source) [6].

4.   System Considerations for Space

The systems that are necessary for a basic space based lasers are (Figure 12):

- Fuel Source
- Energy Convertor
- Energy Storage
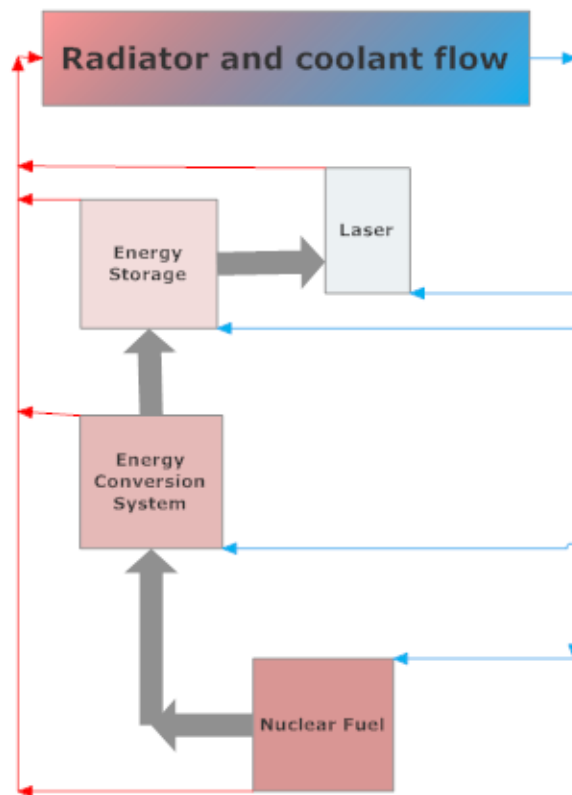- Laser
- Radiator and Coolant Flow System

Figure 12. Basic systems used in a space based laser system. In the case of an electrical pumped laser, the nuclear fuel would produce heat, the energy convertor would be a Stirling engine, the energy storage would be a capacitor bank & associated power circuits and the laser would be its own system including optics, gas flow systems, tracking electronics, etc.

Beginning with the radiator, materials which weigh approximately 50 milligram/square meter have been assumed in a study of solar satellites. Thus an assumption that a radiator would weigh around 0.1 kg/square meter (including structural components) is reasonable. If the system had to dissipate 800 MW thermal with an operating temperature of 673 K , to space with a sink temperature of 4 K, the required area of the radiator can be calculated from the Stefan-Boltzmann Equation,

$$P = \epsilon \sigma A(T_{hot}^4 - T_{ambient}^4) \qquad (16)$$

where, P is power radiated, ε is the emissivity (for an ideal material ε=1), σ= 5.6703x10^{-8} Wm^{-2}K^{-4}, $T_{hot}^4 = 673$, $T_{ambient}^4 = 4$.

The area of the ideal radiator would be 58,500 m^2 with a mass of 5,850 kg.

For an electrically driven laser, the total mass of the system can be estimated. The mass of the fuel has been discussed ($\gtrsim$100 kg), but the means to convert the energy from the fuel to the energy form used to drive the laser is complex. If a nuclear reactor were used as a heat source and a Stirling engine were used to convert the heat to electricity (with 30% efficiency), the mass of the reactor structure and the Stirling engine would be about 16,000 kg. The mass of the capacitors and power electronics for an electrically driven laser about 200 kg. The mass of the laser and auxiliary systems is about 1000 kg. Thus the total mass would be ~17,300 kg.

The advantage of using an NPL is that the mass of the energy convertor can be eliminated. Thus NPLs can weigh as little as 2,000 kg (for semiconductor direct nuclear driven laser) as previously discussed.

5.   Conclusions

NPL technology was part of the U. S. Department of Defense research agenda from 1983 to 1990 as part of the Strategic Defense Initiative (SDI). When NPL research lost its priority, progress in the U. S. stagnated. In the meantime, researchers from the Former Soviet Union have continued research in NPLs. Other countries (e.g., China) have shown interest [1] and have developed working relationships with Russia to enhance the Chinese program [2]. The primary focus of both the Russian and Chinese program openly appears to be the 1.73 μm and 2.03 μm Xe laser because of the laser's 2% efficiency and low pumping power density. This does not necessarily mean that there are not other efforts on classified NPL lasers systems. It simply means that this is only what Russian and Chinese scientists have openly published. Clearly it is desirable to have higher NPL efficiency thus advanced NPL concepts are necessary to achieve these goals. The concern expressed in the congressional report 851 [2] is the technology has military applications in space defense and missile defense. This is a valid concern because of the scalability of NPL technology, specifically if the laser is directly coupled to the reactor fuel (like the design shown in Figure 11). The case made in this paper is that NPL/reactor technology can be constructed from unit cells which may be assembled to the desirable size to achieve the needed power level. Thus the requirements for BMD are achievable.

It is more interesting to consider non-military applications however. High power/high energy lasers have very important non-military applications. One example is for a device which can deflect asteroids. The requirements for asteroid deflection are stringent, (>100 MW CW, capable of operating for years and the ability to beam energy on the asteroid at a high enough intensity to cause ablation of matter). NPL technology is promising for asteroid deflection because of its scalability to the very high power levels needed. As discussed, through the use of volume sources, energy focusing, photolytic pumping and semiconductor lasers, it is feasible to achieve system sizes for asteroid deflections which can be launched with present rocket technology. The scalability and reduced mass of NPL technology is important for other non-

military in other applications including space propulsion [44, 45], power transmission [46], and asteroid mining.

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