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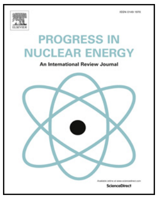

Thermal to optical energy conversion: A multi megawatt carbon dioxide laser driven by an extremely high temperature gas cooled reactor

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ABSTRACT

In the conversion of ionizing radiation into energy, the production of heat is the most common first step in energy conversion systems, but it is also possible to use ions and excited states as the first step. The difference being that nearly all of the energy content of ionizing radiation is converted to heat but only 40–50% of the energy content of ionizing radiation is converted into ions and excited states. Conversion of the energy contained in ionizing radiation into ions and excited states starts out at a considerable disadvantage. Nuclear-pumped lasers have typically depended on the conversion of ionizing radiation into ions and excited states as a first step. Among the reasons that nuclear-pumped lasers have had low system efficiencies (1–2.5%) is the considerable inefficiencies in producing ions and excited states from ionizing radiation. A nuclear-pumped laser system which uses heat produced from the energy content of ionizing radiation as the driver for the laser system is described in this paper. The conversion of heat into vibrational states in molecular nitrogen allows energy to be stored in a long lived molecular state which can then be transported spatially where its energy is collisionally conveyed to carbon dioxide molecules in a resonance transfer process to produce the carbon dioxide upper laser level. The carbon dioxide laser emits a laser beam with a wavelength centered at 10.4 μm. The nitrogen vibrational state and its resonance conversion into the carbon dioxide upper laser level is one of nature's most efficient processes in laser physics (with laser efficiencies approaching ~20% primarily being driven by the resonance process-extremely high for a laser). The laser system described here takes advantage of this highly efficient mechanism for conversion of thermal energy to optical energy. The feasibility of using nuclear rocket core technology for the generation of high temperature gas flows to power this thermal to optical conversion process is described. This study indicates that the thermal to optical conversion process can lead to a carbon dioxide laser with efficiencies on the order of 7% or perhaps better. Such a system would have potential applications in power beaming, space propulsion, asteroid mining, asteroid deflection and potential military applications.

1. Introduction

This paper introduces a thermal to optical energy conversion system based on a Nuclear-Pumped Laser (NPL) coupled to a nuclear reactor concept capable of producing a Continuous Wave (CW) beam energy of tens of MW (referred to in this paper as Dragon). The concept of a Nuclear-Pumped Laser (NPL) was first proposed in 1963 by Herwig (Miley et al., 1989). Traditionally, a NPL is thought of as the utilization of ionizing radiation from nuclear reactions as the means of providing ionization and excitation to drive a laser. The first NPLs used the gamma rays from a thermonuclear explosion by teams from Lawrence Livermore National Laboratory (Ebert et al., 1974) and Los Alamos National Laboratory (Lyons et al., 1974). In 1975 the first NPL (based on a molecular carbon monoxide) utilizing neutron capture reactions to produce ions from an operating nuclear reactor was discovered (McArthur and Tollefsrud, 1975). Approximately 50 NPLs driven by ions and excitation produced by products from neutron capture events using nuclear reactors as neutron sources have been reported (Boody et al., 1978; Miley, 1977; Miley et al., 1989; Prelas, 2016; Prelas et al., 1988, 2014; Prelas and Loyalka, 1981). The neutron capture reactions used in these experiments were uranium-235, boron-10 or helium-3 (Equations (1)–(3)). It should be noted that in using helium-3 or boron-10 there is an energy investment made from the nuclear reactor to create a neutron (e.g., 210 MeV for every 2.44 neutrons produced).

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Thus, if it takes two fission reactions to produce enough neutrons so that one is captured by the helium-3 or boron-10, then there is an energy investment of 420 MeV per neutron that is captured. This makes the use of helium-3 or boron-10 energy inefficient (i.e., 0.76 MeV is released by helium-3 thus the energy efficiency is 0.76/(420 + 0.76) = 0.001806; 2.35 MeV is released by boron-10 thus the energy efficiency is 2.35/(420 + 2.35) = 0.00556). On the other hand, uranium-235 can be part of the core design, thus making it energy efficient because all of the fission fragment energy can be coupled to the laser medium depending on the interface between the uranium-235 fuel and the laser medium (i.e., 165 MeV are carried by the fission fragments thus the energy efficiency is 165/210 = 0.786) (Prelas et al., 2014). Additionally, a number of studies have demonstrated that self-critical coupled reactor/laser systems are feasible (Boody and Prelas, 1992; Gu et al., 1988; McArthur et al., 1977; Prelas, 1989, 2016; Prelas et al., 1985; Rodgers, 1979; Watermann and Prelas, 2013). In these studies, many issues were discussed which must be overcome in order to build self-critical coupled reactor/laser systems. One of the primary issues is the pumping power density which high power/high energy lasers need. Reactor pumping is somewhat limited in the power density that can be supplied (Prelas, 2016; Prelas et al., 2014). If a uranium-235 foil is used to interface with the laser, a fast burst reactor (with a pulse width of 0.2 ms FWHM and a peak flux of 1×10^{17} thermal neutrons $\mathrm{cm^{-2}\,s^{-1}}$) has a theoretical maximum power density of $4740\,\mathrm{W\,cm^{-3}}$, a pulsed TRIGA reactor (with a pulse width of 10 ms FWHM and a peak flux of 2×10^{16} thermal neutrons $\mathrm{cm^{-2}\,s^{-1}}$) has a theoretical maximum power density of $119\,\mathrm{W\,cm^{-3}}$, and a steady-state reactor (the Advanced Test Reactor for example has a peak neutron flux of 1×10^{15} thermal neutrons $\mathrm{cm^{-2}\,s^{-1}}$) has a theoretical maximum power density of $1.06\,\mathrm{W\,cm^{-3}}$. If uranium-235 is mixed with the laser medium volume (e.g., encapsulated uranium in a C60 cage-uranofullerene (Mencin and Prelas, 1992)), the fast burst reactor has a theoretical maximum power density of $44{,}300\,\mathrm{W\,cm^{-3}}$, the pulsed TRIGA reactor has a theoretical maximum power density of $1100\,\mathrm{W\,cm^{-3}}$, and the steady-state reactor has a theoretical maximum power density of $44.3\,\mathrm{W\,cm^{-3}}$. Unfortunately, the most attractive high-power high-efficiency lasers require power densities greater than maximum available power density from a reactor pumped system (e.g., $44{,}300\,\mathrm{W\,cm^{-3}}$ - a fast burst reactor with a laser that uses C60 cage-uranofullerene particles mixed in with the laser medium (Prelas, 2016)). The self-critical nuclear pumped laser studies were limited to less desirable lasers with efficiencies on the order of one to two percent (having power density requirements of about $10\,\mathrm{W\,cm^{-3}}$ or lower) (Boody et al., 1978; Felty et al., 1993; Melnikov et al., 2008; Miley et al., 1989; Prelas, 2016; Ulrich et al., 2009; Watermann and Prelas, 2013).

$$ {}^{3}_{2}\mathrm{H\ e} + {}^{1}_{0}n_{th} \rightarrow {}^{3}_{1}T + {}^{1}_{1}p^{+} + 0.76\,MeV \tag{1}$$

$$ {}^{10}_{5}B + {}^{1}_{0}\mathrm{n_{th}} \rightarrow {}^{7}_{3}Li + {}^{4}_{2}He + 2.35\,MeV \tag{2}$$

$$ {}^{235}_{92}U + {}^{1}_{0}\mathrm{n_{th}} \rightarrow {}^{A_h}_{Z_h}f_h + {}^{A_l}_{Z_l}f_l + \nu_f \cdot {}^{1}_{0}\mathrm{n_f} + 210\,MeV \tag{3}$$

where n_{th} is a thermal neutron, ff_h is a heavy fission fragment, ff_l is a light fission fragment, ν_f is the statistical number of fast neutrons released per uranium-235 fission (2.44), $\mathrm{n_f}$ is a fast neutron.

There are alternative ways to use nuclear energy to drive high-power/high-efficiency lasers without having subsystems that will increase the complexity, the size and the mass of the coupled reactor/laser (e.g., using a Rankine cycle to produce electricity which is then used to electrically drive the laser (Day and Kennedy, 2010)). All NPLs discovered to date use the creation of ion pairs and excitation by ionizing radiation as a first step. The efficiency of this step is typically 35%–58% dependent on the medium (e.g., solid, liquid, gas, type of gas, etc.) and the ionizing radiation (e.g., ions) (Prelas, 2016). Thus, ionization efficiency is an upper efficiency bound for this type of laser. In contrast, the energy from nuclear reactions can be converted to heat at nearly 100% efficiency. Thus, a method based solely on thermal effects has potential efficiency advantages with the right laser system. It is feasible to thermally drive a $\mathrm{CO_2}$ laser (Fein et al., 1969) and a $\mathrm{CO_2}$ laser is known for its high-power and high-efficiency. In this paper, a high-power and high-efficiency $\mathrm{CO_2}$ laser using an extremely-high temperature gas-cooled reactor as a thermal pumping source is described. In order to achieve the high temperatures needed for thermal pumping, a reactor fuel made with ZrC, UC and NbC is examined for operating temperatures of 2000 K and beyond (Lanin and Fedik, 2011). The operating temperature of the laser is chosen as 600 K even though a much lower temperature is desired for beam quality. The reason for this choice is to have a high residual gas temperature which could drive a secondary energy conversion cycle such as a Stirling engine to produce electrical power. A reactor system which could produce a beam capable of focusing power on a close in object plus produce electrical power would have value in applications such as asteroid mining (Prelas, 2016).

2. Reactor engineering

The goal of this reactor is to produce a very high temperature working fluid (e.g., $\mathrm{N_2}$) and inject the high temperature fluid as quickly as possible into a laser cavity, so this design is more like a nuclear rocket than a power reactor plant (Auweter-Kurtz et al., 2008; Vadim and Vladimir, 2007). This aspect of the design is reflected in some of the details of the core configuration. The materials questions are complex because the goal is to sustain steady-state temperatures of 2000 K or more. The key to designing the core is in the use of high temperature fuels and high temperature structural materials. Carbides are more fragile and not as thermally conductive as typical Pebble Bed Reactor (PBR) TRISO materials, but what is gained in using carbides is a far higher operating temperature (Lanin and Fedik, 2011).

The next step of the study addresses the core criticality, gas flow parameters, and the heat transfer characteristics of the core. A typical PBR contains hundreds of thousands of pebbles that move through the core as it operates. One must find a way to calculate the critical properties given the stochastic nature of the fuel configuration. Direct simulation is difficult, as it requires sophisticated algorithms to produce stochastic fuel geometries, and large amounts of computational overhead to execute. Computational Fluid Dynamic (CFD) simulations have been performed where all manners of factors are calculated such as compressibility, eddies, spatially dependent temperatures, densities, and pressures (Becker and Laurien, 2003; Hassan and Dominguez-Ontiveros, 2008; Oukil et al., 2013). Analytic estimations that account for these parameters are few and not as reliable as CFD. To circumvent these issues the following approximations are made:

- The core is modeled as a porous medium for flow and heat transfer calculations.
- The pebbles are stacked in Body Centered Cubic (BCC) pattern. This allows for an easy calculation of the porosity (the volume in the core not taken up by the pebbles) to be $\varepsilon = 0.32$.
- The $\mathrm{N_2}$ gas when flowing through the core is assumed as being incompressible.
- $\mathrm{N_2}$ will be considered an ideal gas for calculating the density.
- For criticality calculations, the core will be homogenized where the volume is a mixture of the atom fractions based on the choice of pebble structure.

The actual distribution of pebbles in the core will be random, but the BCC structure is the most accurate and straight forward model for this case (Pilehvar et al., 2013). The ideal gas law is sufficiently accurate for this situation. Additional corrections can be made, such as the virial expansion. These methods give a difference of less than 1% for density calculations.