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High Energy Laser for Space Debris Removal

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High Energy Laser for Space Debris Removal: Executive Summary

The National Ignition Facility (NIF) and Photon Science Directorate at Lawrence Livermore National Laboratory (LLNL) has substantial relevant experience in the construction of high energy lasers, and more recently in the development of advanced high average power solid state lasers.[1-3] We are currently developing new concepts for advanced solid state laser drivers for the Laser Inertial Fusion Energy (LIFE) application,[4] and other high average power laser applications that could become central technologies for use in space debris removal.

The debris population most readily addressed by our laser technology is that of 0.1-10 cm sized debris in low earth orbit (LEO). In this application, a ground based laser system would engage an orbiting target and slow it down by ablating material from its surface which leads to reentry into the atmosphere, as proposed by NASA's ORION Project.[5,6] The ORION concept of operations (CONOPS) is also described in general terms by Phipps.[6] Key aspects of this approach include the need for high irradiance on target, 10^8 to 10^9 W/cm^2, which favors short (i.e., picoseconds to nanoseconds) laser pulse durations and high energy per pulse (~> 10 kJ). Due to the target's orbital velocity, the potential duration of engagement is only of order 100 seconds, so a high pulse repetition rate is also essential. The laser technology needed for this application did not exist when ORION was first proposed, but today, a unique combination of emerging technologies could create a path to enable deployment in the near future.[3,4]

Our concepts for the laser system architecture are an extension of what was developed for the National Ignition Facility (NIF), combined with high repetition rate laser technology developed for Inertial Fusion Energy (IFE), and heat capacity laser technology developed for military applications. The "front-end" seed pulse generator would be fiber-optics based, and would generate a temporally, and spectrally tailored pulse designed for high transmission through the atmosphere, as well as efficient ablative coupling to the target. The main amplifier would use either diode-pumped or flashlamp-pumped solid state gain media, depending on budget constraints of the project. A continuously operating system would use the gas-cooled amplifier technology developed for Mercury,[2] while a burst-mode option would use the heat capacity laser technology.[3]

The ground-based system that we propose is capable of rapid engagement of targets whose orbits cross over the site, with potential for kill on a single pass. Very little target mass is ablated per pulse so the potential to create additional hazardous orbiting debris is minimal. Our cost estimates range from $2500 to $5000 per J depending on choices for laser gain medium, amplifier pump source, and thermal management method. A flashlamp-pumped, Nd:glass heat-capacity laser operating in the burst mode would have costs at the lower end of this spectrum and would suffice to demonstrate the efficacy of this approach as a prototype system. A diode-pumped, gas-cooled laser would have higher costs but could be operated continuously, and might be desirable for more demanding mission needs. Maneuverability can be incorporated in the system design if the additional cost is deemed acceptable. The laser system would need to be coupled with a target pointing and tracking telescope with guide-star-like wavefront correction capability.

High Energy Laser for Space Debris Removal: Design Basis

In the early 1970s, LLNL began building a series of increasingly energetic laser systems, including Cyclops, Argus, Shiva, Nova, Beamlet, and now the National Ignition Facility (NIF).[1] These are high energy, single shot lasers using flashlamp-pumped, neodymium-(Nd)-doped laser glass as the optical gain medium. In recent years we began to develop diode-pumped solid-state laser (DPSSL) systems to increase the efficiency and repetition rate to levels required for a proposed Laser Inertial Fusion Energy (LIFE) application.[2,4]

In many ways, the NIF is a prototype of our baseline LIFE laser concept. As with the NIF, the LIFE laser concept consists of a large number of individual beam-lines or beamlets. We would duplicate NIF's basic multi-pass architecture with a few minor modifications to optimize performance. In addition, to enable high-average-power operation, we replace the NIF's passive cooling system with high-speed helium gas to remove heat from active laser components, as demonstrated in LLNL's Mercury laser[2] and shown in Figure 1a. To achieve required laser efficiency >10%, we also replace the NIF's flashlamps with a laser-diode pumping system. One of Mercury's eight 100 kW, 900-nm pump-diode arrays is shown in Figure 1b. For the LIFE laser, an increase in repetition rate by nearly five orders of magnitude compared to NIF results in average output power of more than 100 kW (at 1053-nm) per LIFE beamlet.

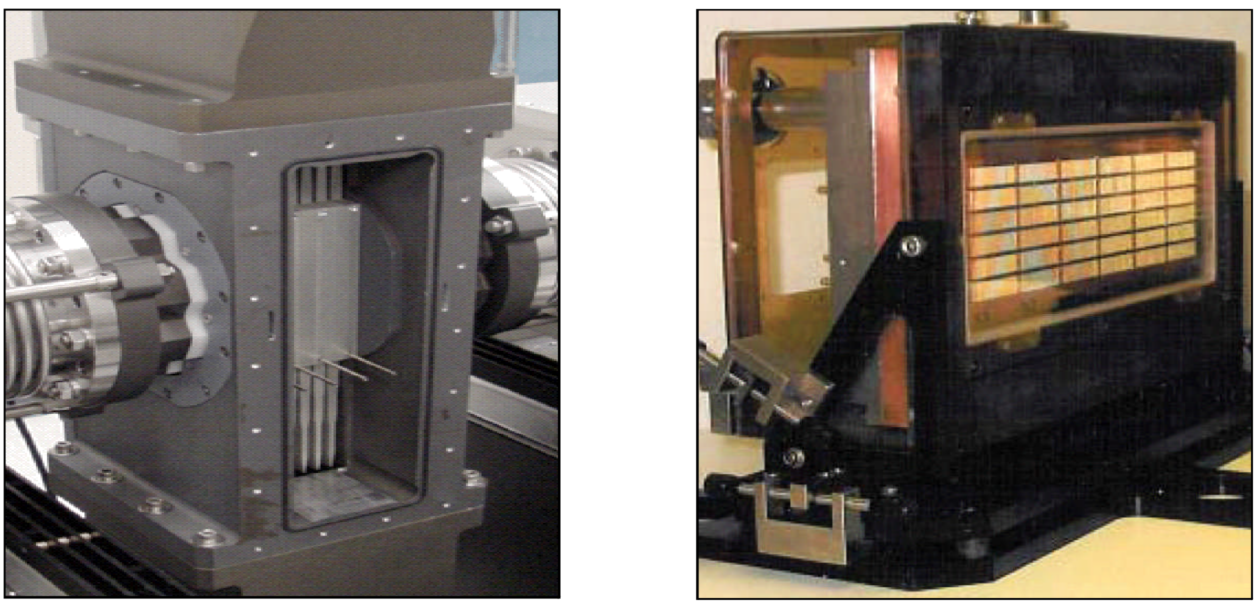

Figure 1. a) Mercury helium gas cooled amplifier, and b) 100 kW 900-nm pump diode array.

Dissipation of thermal energy in the laser amplifiers, and the Pockels Cell switches is an important issue for continuous operation, but if active media cooling systems are not included, a less expensive system could operate in "heat-capacity" mode for up to several seconds. The required laser wall-plug efficiency for LIFE is ~> 10%. With laser diode pumping, we believe that efficiencies greater than 12.6%, after frequency conversion, can be achieved (see below). Note that frequency conversion is not likely to be required for space debris removal.

The schematic of a beamline architecture that could be used for space debris removal is shown in Fig. 2. Here, we adopted the NIF beamline architecture because it has performance advantages relative to other architectures, it is well engineered and tested, and it has demonstrated reliable performance for the 192-beamline NIF laser.[1] Since the space debris removal laser operates at high repetition rate (~> 10 Hz) while the NIF laser operates at a few shots per day, designs for the amplifiers and Pockels cell switches need to be modified to improve efficiency and handle waste heat. These modifications are described below and include flowing He gas over thin laser slabs and Pockels cell crystals. To reduce Pockels cell switching voltage, improve pumping efficiency and to reduce vibrations of the laser slabs, the beam aperture for the amplifiers is reduced to 20 by 40 cm, compared with 40 by 40 cm for NIF. Additional advantages of using a smaller aperture include reduced losses due to amplified spontaneous emission (ASE) in the laser slabs, higher overall efficiency, and reduced costs for fixtures needed to fabricate optical components.

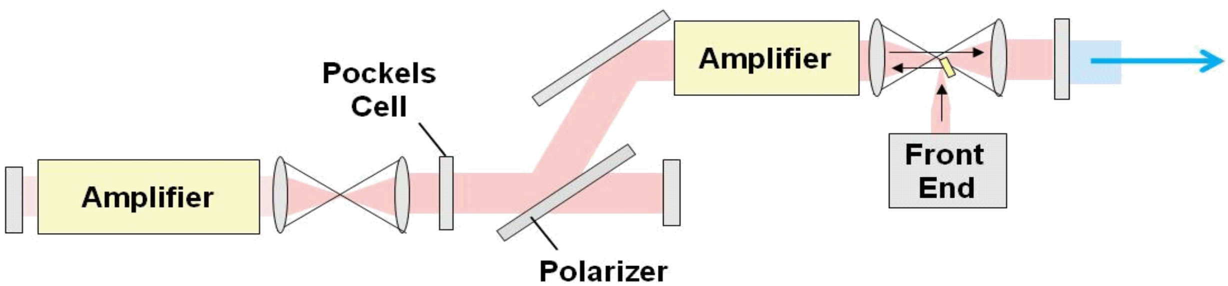

Figure 2. Potential beamline architecture for space debris removal.

In Figure 2 pulses from the front end are injected in the far field of the transport spatial filter. After being collimated by the transport spatial filter lens, the beam passes through the booster amplifier, reflects off a mirror, reflects off the polarizer, and passes through the Pockels cell, cavity spatial filter, and cavity amplifier. After reflecting from the cavity end mirror, which might be a deformable mirror for correcting wave-front distortion, the pulses pass a second time through the cavity amplifier, cavity spatial filter, and Pockels cell. As the Pockels-cell voltage has been applied by this time, the Pockels cell rotates the beam polarization by 90º, and the beam is transmitted through the polarizer. After reflecting off from the second cavity end mirror, the beam passes through the polarizer, Pockels cell (which rotates the polarization back to its original orientation), cavity spatial filter, and cavity amplifier again. After reflecting from the first cavity end mirror again, the beam makes a fourth and final pass through the cavity amplifier, cavity spatial filter, and Pockels cell, which is now at low voltage and does not rotate the beam polarization. The beam reflects off the polarizer, reflects off a mirror, and passes a second time through the booster amplifier. It then propagates through the transport spatial filter, where it is magnified anamorphically to a final 40 by 40 cm^2 aperture size.

Some advantages of multi-passing the main amplifier include increased extraction efficiency, elimination of preamplifier sections that would add cost and increase building space, and reduced front-end size. Four passes are sufficient for achieving most of the benefits available from multi-passing as the required front-end energy is <1 J. At this energy, cost of the front end is small relative to the cost of the rest of the system. Two passes would be insufficient, however, since the required front-end energy would be >100 J, and front-end costs would be many times larger. Achieving four passes with this architecture, however, has the added cost of using a full-aperture Pockels cell switch.

Thermal energy is deposited in glass laser slabs due to non-radiative transitions between Nd^{3+} energy levels. It is also deposited in deuterated potassium di-hydrogen phosphate (DKDP)

Pockels cell crystals due to residual hydrogen impurity absorption at the fundamental 1.05-µm wavelength. Heat is removed from these optics by transfer to high-velocity helium gas flowing in channels between the “slablets” as depicted in Figure 3. As heat in the optics flows toward their surfaces, the temperature is highest in their center and lowest at their surface. Thermal expansion of the center of the optics then puts the surfaces into mechanical tension. At the surface, residual cracks from the optics finishing process can propagate and lead to catastrophic crack growth if the tensile stress exceeds a critical value that depends on the material’s fracture toughness. Surface tensile stress is reduced by reducing slablet thickness, thereby reducing the temperature differential between the center of an optic and its surfaces.

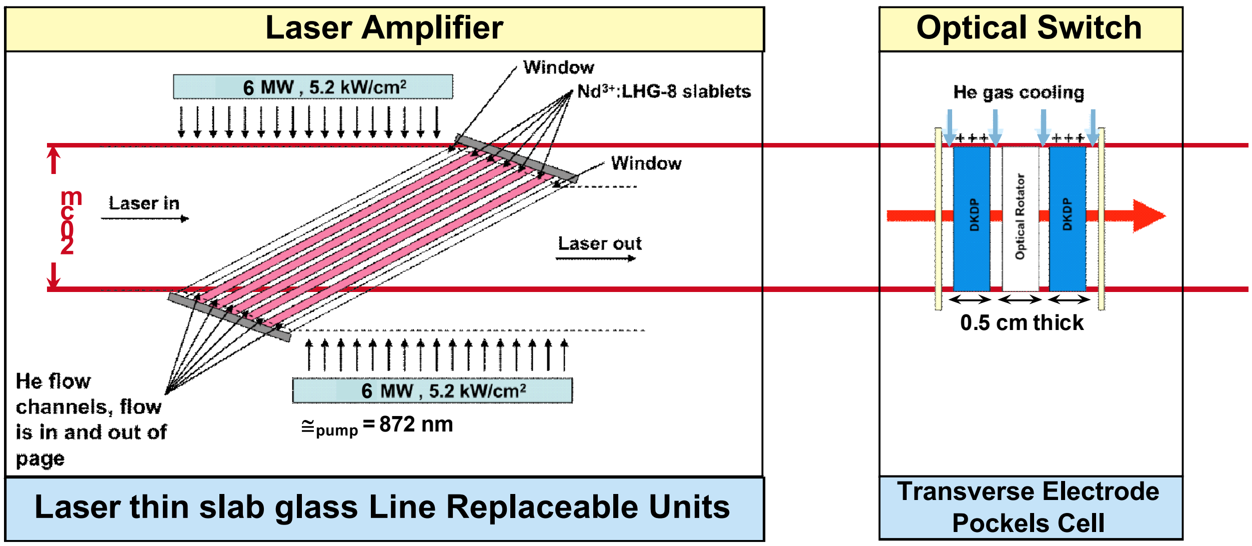

Figure 3. Gas cooled amplifier and Pockels cell concepts.

Control of thermal gradients and their effects on wavefront distortion and beam depolarization is important. Contributions by Pockels cells can be kept small by using highly-deuterated DKDP crystals, to reduce absorption of laser light and its associated heating. Preliminary finite element calculations show that contributions by laser slabs can also be kept small, by pumping slabs uniformly and by flowing cooling gas uniformly over slab surfaces. When pump-light distributions are non-uniform, however, significant wavefront distortion and depolarization can occur. Some pump non-uniformity may be advantageous. For example, laser efficiency can be increased by distributing pump light away from the edges of the slab where the extracting beam does not propagate. Greater wavefront distortion can be tolerated by using a deformable mirror to correct wavefronts. Similarly, greater depolarization can be tolerated by applying birefringence-compensation techniques. Detailed modeling to optimize tradeoffs between beam quality and efficiency, taking into account possible wavefront-correction and birefringence-compensation methods, will be an important part of a detailed laser design process.

With the current composition of NIF amplifier glass and its finishing specifications (i.e., scratch-and-dig limits), we find that the amplifier slabs should be reduced in thickness to eliminate the potential for surface crack growth during high-average-power operation. Thus, NIF amplifier slabs, normally 4-cm in thickness, are thinned into five slablets of 8-mm thickness each, as shown in Figure 3. Windows are added beside the outer slablets to contain the high-speed helium cooling gas flow. Laser diodes operating at 872-nm wavelength pump directly into the $^4F_{3/2}$ upper laser level of Nd^{3+}. The pump diode arrays operate at a spatially averaged, temporal peak irradiance of 5.2 kW/cm^2. The total peak diode power is 6 MW on each side of the amplifier.

The need to use thinner amplifier slabs is driven by the relatively low thermo-mechanical fracture-toughness of the NIF's current phosphate glass compositions and the current scratch-and-dig finishing specifications. We think that new glass compositions and/or advanced finishing technology can change or eliminate the requirement to reduce slab thickness. The development of new glasses and finishing technology will be part of the LIFE Laser development process.

Efficient extraction of the energy stored in the main amplifier is achieved with a Pockels cell electro-optic switch. A Pockels cell is simply an electrically driven switch that controls the polarization state of light passing through it. When coupled with a polarizer, the light path is altered, allowing multi-pass extraction.

The operating voltage and thermal loading constrain the design of the Pockels cell. The voltage required to rotate the polarization by 90^o is known as the half-wave voltage. In a transverse Pockels cell (where the applied voltage is orthogonal to the light propagation direction), the half-wave voltage is proportional to the distance between the electrodes and inversely proportional to the crystal thickness. The Pockels cell is designed with the constraints of ensuring that the drive voltage required to switch the device falls within the realm of possibility for the desired repetition rate and that the center-to-edge thermal gradient in the Pockels cell crystal is below the fracture limit of the crystal. The design criteria of an aperture-scalable, He gas-cooled, high-average-power switch has already been discussed.[7] For the electro-optic crystal, we propose using DKDP with a deuteration level between 95 – 99.9%. DKDP exhibits a residual near-infrared optical absorbance, which varies between 0.003/cm and 0.001/cm, for 95% and 99.9% deuterated crystals, respectively.[8] In contrast to the gain medium, the thermal load on the Pockels cell is quite modest and can be readily removed by near room temperature, room pressure subsonic helium flows.

To eliminate static birefringence, the individual DKDP crystals are matched in thickness to one another within a few microns. While this represents a strenuous optical specification, these tolerances are met on crystalline parts machined using diamond turning and magneto-rheological finishing. Solid-state high-voltage power supplies, similar to the supplies already used for the plasma electrode Pockels cell on NIF, have already demonstrated operation at 10-Hz repetition rates and can be scaled to the necessary (~ 100-kV) voltage.

Other large aperture optics, in addition to DKDP, are required. The incident horizontally polarized light must be rotated 45 degrees both before and after the Pockels cell crystals. In addition, the equivalent of a 90 degree optical rotator must be used in the center of the Pockels cell. Two crystals are potentially available as the basis of these optical elements. Hydrothermally grown quartz is available with apertures of approximately 20 cm, whereas the current design requires a 20 by 40-cm aperture. While it is likely that hydrothermally grown quartz can be scaled to the final aperture, quartz can be easily optically bonded to provide a segmented window of the desired aperture size. In addition to quartz, high optical quality sapphire is currently available for the desired aperture. Again, precision magneto-rheological finishing of sapphire will allow the manufacture of large aperture wave-plates necessary for the Pockels cell operation.

NIF's flashlamp pumping of the main slab amplifiers will be replaced with arrays of laser diodes in the high average power laser. This allows us to take advantage of an order of magnitude increase in electrical-to-optical energy conversion efficiency. While increases in laser diode efficiency and power make this development technologically feasible, it would not be economically feasible without a substantial reduction in the cost of laser diodes. Fortunately, laser diode costs will drop rapidly as the market for their use grows. At present pump diodes cost a few dollars per Watt of peak power. Recent LLNL cost estimates indicate that the cost can drop to ~ $0.1 per Watt when quantities required to build a prototype LIFE laser and/or a space debris removal laser system are purchased.

For a LIFE laser driven power plant pump diode cost needs to decrease to of order $0.01 per Watt. The potential for this level of cost reduction in laser diode manufacturing can be better understood by comparison with the process for making GaAs integrated circuits (ICs) in the cell phone industry. There is a half-dozen or so high frequency GaAs ICs in every cell phone. The growth of GaAs crystals, production of wafer substrates, epitaxial growth and patterning of layers is very similar to laser diode production technology. If one estimates the cost per unit area of GaAs IC chips and divides by the power per unit area that can be obtained from laser diodes, the answer is close to $0.01 per Watt, in good agreement with our cost estimates for high volume laser diode manufacturing. Moreover, an estimate of the total volume of GaAs ICs produced to date shows that the area of GaAs substrates used in the world's two billion cell phones already exceeds that needed for the first LIFE demonstration power plant (~ 40 billion Watts).

We have made a preliminary estimate of the cost of a space debris removal laser beamline based on this technology. The basis for our cost estimate is primarily actual costs for the NIF laser. However, adjustments have been made for active cooling of laser slabs and diodes and for using diodes to pump the slabs rather than flashlamps. Additionally, we have applied scaling factors for variations in aperture size and repetition rate. For these calculations, diode costs were set at $0.1/Watt. Costs for electrical power-conditioning are based on a new circuit designed specifically to drive these laser diodes. Given the assumptions, our cost estimates range from $2500 to $5000 per J depending on choices for laser gain medium, amplifier pump source, and thermal management method. A flashlamp-pumped, Nd:glass heat-capacity laser operating in the burst mode would have costs at the lower end of this spectrum would suffice to demonstrate the efficacy of this approach as a prototype system. A diode-pumped, gas-cooled laser would have higher costs but could be operated continuously, and might be desirable for more demanding mission needs.

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