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LASER REQUIREMENTS SPECIFIED FOR ADVANCED LASER-FUSION EXPERIMENTS

Lasers based on atomic carbon, oxygen, or heavier members of the same groups of elements seem the most promising types for advanced long-range laser-fusion research, according to our recent studies. Such lasers can be excited either by electronic energy transfer or by absorption of photons, the same excitation mechanisms appropriate to the rare-gas systems we have been studying. Electron-beam excitation (also being studied) is another possibility.

Advanced research into the compression and ignition of inertially confined thermonuclear pellets by laser radiation will eventually require a laser source with specialized characteristics not well satisfied by any known laser system. In particular, this specialized laser will be needed for proving the feasibility of large energy yields and practical applications of laser fusion. Our studies of the projected requirements and inherent limitations on high-energy lasers provide developmental guidelines and help identify potential lasers having some of the required characteristics. Equally important, they allow entire classes of potential lasers to be eliminated from consideration. These requirements and limitations, together with their implications for the laser, are listed in Table 3.

The considerations in this table lead us to seek a laser operating on a forbidden electron transition, preferably in a gas, with high potential efficiency. The lower level of the laser transition should be near the system's ground state. The laser upper level must be resistant to deactivation even at high energy-storage densities for long energy-storage times, and it must be able to be populated efficiently. Initially, all the pulse energy must be stored in the laser upper level because there will be no pumping during the pulse; this consideration favors an atomic transition rather than a molcular system, although molecular systems are not ruled out. A wide energy gap should exist between any populated states of the lasing species and other, higher energy levels or ionization limits; otherwise, excited state absorption from the laser upper level could occur.

As candidate atomic system for such lasers, large regions of the periodic table can be discarded immediately (their properties are unsuitable). From the remaining candidates, we find the closest match to the desired properties among atoms with partly filled *p* shells in which parity forbids allowed transitions between states of the lowest electronic configuration and, also, the promotion of an electron to the next *s* shell requires so much energy that the influence of these higher-lying states is negligible. Atoms with two or four *p* electrons in their outer shell look most promising, although those with three *p* electrons may also be suitable. The former include carbon, oxygen, and heavier members of the same groups of the periodic table – silicon, sulfur, germanium, selenium, etc. With the unimportant exception of their fine structure, all these atoms have similar energy level structures and transition probabilities.

As a model of this type of laser system, we have analyzed the ^1S-^1D (557.7-nm) green line of atomic oxygen found in auroras.[11] The conclusions from this analysis (given below) apply qualitatively to the other atoms.

Efficient pumping of the laser upper level is required. Since transitions from the atomic ground state to potential laser upper states are forbidden in these atoms, direct electron collision excitation or optical pumping of the atoms does not look promising. It is quite possible, however, to have an allowed electronic transition from a molecular state that dissociates to produce an atom in the upper laser level. These allowed pumping transitions appear the most practical means to pump the laser (some dissociative path is required in any case because these elements do not exist as atomic gases at any reasonable temperature). The required pumping transitions lie at energies of perhaps 6 to 12 eV (wavelengths of 200 to 100 nm) and can be excited either by electronic energy transfer in collisions or by photon absorption.

Our recent experimental and theoretical investigations of rare-gas systems apply directly to both the collision-transfer and photolytic processes because these rare-gas systems can serve either as efficient fluorescers or as energy donors in selective collisional energy-transfer processes. We have experimentally verified such efficient energy transfer in a laser for a xenon excimer laser operated in argon-xenon and krypton-xenon mixtures. It is therefore natural to pursue this technology while exploring the candidate species for atomic gas lasers.

Electron-beam excitation of gases, either directly in the laser or in a scintillator for optical pumping of

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Table 3. Requirements, limitations, and resulting implications for potential lasers for advanced laser-fusion experiments

Requirement	Reason	Implication for the laser
REQUIREMENTS FOR COUPLING TO THERMONUCLEAR PELLET		
Short wavelength (~600 nm or less)	To provide optimum coupling of energy to the pellet	Laser must operate on an electronic transition.
Output 1 MJ in 0.1 ns	To establish conditions for efficient thermonuclear burn	Entire pulse energy must be stored in laser upper level; pumping or relaxation from other levels must be insignificant in 0.1 ns.
REQUIREMENTS FOR PRACTICAL APPLICATIONS		
High efficiency (at least 5%)	To satisfy requirements for any practical application (i.e., commercial power generation).	Energy must be selectively transferred from storage (electrical) to laser upper level; losses such as absorption of laser radiation from this level to higher level must not occur; energy extraction must be efficient (for saturated amplifier).
Pulse rate about 100 per second		Pulse rate requires a gas laser with convective cooling (large solid-state lasers cannot be cooled quickly).
Low cost and low maintenance		Replacement of expensive components should be infrequent; this tends to favor gas lasers.
Smallest possible size	To reduce the high cost of optics and other components and the difficulty of transferring large laser pump energies over long distances in very short times	High energy-storage density is desirable; collisions of excited states should not lead to de-excitation.
LIMITATIONS IMPOSED BY PROPERTIES OF MATTER		
Wavelength longer than ~300 nm	To prevent severe two-photon absorption at shorter wavelengths in all optical materials at the power levels (10^{14}-10^{15} W/m^2) generated by the laser	Rare-gas dimer (Kr_2^* and Xe_2^*) lasers, though potentially efficient, are not suitable.
Energy flux in pulse less than 10^4-10^5 J/m^2	To prevent damage to optical components; flux in solid-state lasers with long beam distances in high-density material need to be near 10^4 J/m^2 to avoid self-focusing and damage; low-density gas lasers will pass fluxes nearer the optics surface damage limit at 10^5 J/m^2	For efficient energy extraction, laser must saturate at fluxes of at least 10^4-10^5 J/m^2. Since saturation flux $\approx h\nu/\sigma$, stimulated-emission cross section σ for a 500-nm laser should be at least 1-10 pm^2.

Table 3 (continued).

Requirement	Reason	Implication for the laser
LIMITATIONS IMPOSED BY PROPERTIES OF MATTER (continued)		
Lowest small-signal gain consistent with above flux limitation	To suppress parasitic oscillations and superfluorescence, which deplete the energy stored in the laser	Stimulated-emission cross section must be as small as possible consistent with previous limitation (~1 pm^2); thus the laser transition should be a forbidden optical transition, since allowed transitions have $\sigma \approx 0.01$ nm^2.
Inversion lifetime (energy storage time) as long as possible and longer than 1 μs	To reduce the engineering complexity required for transferring ~10 NJ of energy into the laser medium	Laser upper level must be resistant to deactivation and free of other loss mechanisms.

the laser using, for example, rare-gas excimer radiation, is a very versatile technique for depositing large energies in high-density gases on a very short time scale. We are also pursuing this research. Current theoretical and experimental activity is directed toward optimizing such source parameters as pulse length, electron energy, and current density for efficient excitation of rare-gas-excimer fluorescence and other laser excitations. For this purpose we have installed an electron-beam accelerator especially designed for laser excitation experiments. This machine is similar in energy and pulse length to the one described on page 10 but differs in beam geometry; for a better match to the geometry of typical laser systems, the beam emerges as a flat sheet rather than a circular cylinder. We are using the new accelerator in various energy-transfer experiments involving nitrogen and the rare gases as donors.