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LASER SYSTEMS FOR LASER FUSION

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ABSTRACT

Successful development of a laser fusion central power station will require unique lasers having specialized characteristics which are not well satisfied by any known laser materials. It is important at this early time to begin development of a format by which new laser media and the corresponding systems concepts can be evaluated. A "reference" laser fusion power plant design is adopted to estimate required laser system efficiencies. In connection with this design, a hypothetical oxygen auroral line laser is used as a model to delineate the many parameters effecting laser system performance.

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1. INTRODUCTION

Compression and ignition of thermonuclear (TN) pellets in a laser fusion (LF) central power station will eventually require a laser source having specialized characteristics which are not well satisfied by any known laser materials. An analysis of the projected requirements for such a source, taking into account certain inherent limitations on high energy lasers, provides a framework for the development of such a laser and identifies potential lasers having some of the required characteristics. Of equal importance such an analysis allows entire classes of potential lasers to be eliminated from consideration, and identifies critical "systems" associated problems which must be solved as well.

The following analysis is a survey of the requirements of a laser system suitable for use in what might be described as a first generation pure LF power plant as we now understand it. This survey is the first step in developing the analysis format by which new laser media and their corresponding systems application concepts can be evaluated in terms of an operating LF central power station.

2. A LASER FUSION POWER PLANT REFERENCE DESIGN

A "reference" power plant design has been adopted that serves as a potential first generation goal in LF power generation, around which laser and reactor subsystems can be conceptually designed. The laser fusion reactor (LFR) subsystem burns a low \( p_R \) (\( 2 \leq p_R \leq 4 \text{ gm cm}^{-2} \)) pellet and features a low transient first-wall pressure due to the elimination of ablation. A 7 MJ yield from the low \( p_R \) pellet requires a 100 KJ laser pulsed to implode and ignite it. In addition, the laser is required to have a wavelength between 0.3 and 0.6 \( \mu \text{m} \) and peak power of \( \approx 5 \times 10^{14} \text{ watts} \) (the pulse width \( T \) is approximately 10ns with 50% of the energy in the last 100ps). The pellet irradiation symmetry requirement is for 12 beams on target, each containing \( \approx 8 \text{ KJ} \). The conceptual power plant will consist of 10 of these reactor modules operating at 10 Hz, each with its own laser amplifier system (the advantage of this design is that only a 10% power loss will occur when a reactor/laser is taken off-line for maintenance). A power flow diagram for one of the reactor/laser modules is shown in Figure 1.

Power flow in Figure 1 is given in \( \text{MW} \) at each major component. The laser subsystem provides 1 MW average power output (\( E_L \)), 5% of which is coupled into the pellet. The TN burn gain is 1400 with 76% \( (r_n) \) of the energy in the form of 14 MeV neutrons. The blanket contains depleted \( \text{Li} \) containing 4% \( \text{Li}^6 \) to provide a tritium breeding ratio of 1.25 and energy multiplications factor of \( \approx 1.1 \). Basic components of a generalized laser subsystem are shown with efficiencies appropriate for a potential laser medium discussed in a following section. The electrical power output for each reactor/laser module is given by

\[
W_G = Q_n a E_L n_{TC1} (r_n m + r_c + r_x) + E_L n_{TC1} (1 - a) + \frac{E_L n_{TC2}}{n_o} \left( \frac{1}{n_l n_{PC}} - 1 \right) + \frac{E_L n_{TC2} g_{cs}}{n_o n_l n_{PC}}
\]

This simple description of a LF power plant with the component efficiencies shown gives a relationship between \( Q \) and the laser efficiency \( (\eta_L) \) that allows us to speculate about the laser efficiency required in the reference plant design. (For example, the pulsed laser will require a pulsed high energy power supply which presently would consist of a transformer, Marks
Advanced capacitive PFN designs might give an overall power conditioning equipment efficiency of 63%.

A useful parameter for understanding the effects of laser efficiency on plant output and capital cost is the inverse circulating power ratio \(C\). This ratio, the plant output power \(P_o\) divided by the laser systems input power is given in Figure 2 as a function of laser efficiency for various \(Q\). The reference power plant design adopted (Figure 1) \(C = 2.6\) requires a laser operating with an optical power output to electrical power input (conditioned) efficiency of \(\approx 18\%\). The dramatic increase in \(Q\) needed to maintain the desired value of \(C\) at lower laser efficiencies is also demonstrated. What lasers can we expect in the future to achieve these efficiencies?

### 3. THE LASER MEDIUM

As described above, the primary characteristics of our laser include high efficiency, high average power, short wavelength, short pulse widths and high energy. Because of the high average power required and desire to keep costs down, gas lasers appear to be the most attractive at this time. Table 1 gives a summary of the most promising gas lasers presently under investigation. The attributes and problems associated with these lasers are discussed in detail elsewhere. What should be pointed out here is that there is believed to be a trend toward higher energy multiplication \((Q_n)\), with simple pellets, for the shorter laser wavelengths, and that severe optical system design problems arise at the IR and UV wavelengths. Although it might be possible to find efficient laser media that do not exhibit the high stimulated emission cross section and two-photon ionization problems found in Xe, optical system problems at the vacuum UV wavelengths will be severe due to high two-photon absorption coefficients in suitable lenses and windows at fluxes above \(10^{10}\) \(\text{W cm}^{-2}\). At the longer IR wavelengths, higher energy lasers are believed to be required for reasonable gains and again severe problems must be solved to build the lenses and windows needed. This is unfortunate because the CO\(_2\) laser is inherently relatively efficient \((\approx 5\%\) for 1 ns pulses). Efforts are currently underway to develop short pulse systems and to convert the 10.6 \(\mu\)m energy of these lasers to shorter wavelengths.

The output of the ideal laser hypothesized in the reference plant design lies more into the visible spectrum, where it exhibits good pellet coupling; and requires a relatively modest optical system. Consideration of these and all the other requirements given leads us toward favoring a gas laser operating on a forbidden electronic transition with high potential efficiency, implying that the laser lower level should be near the ground state of the system. The laser upper level must be resistant to deactivation for a high density of energy storage and long energy storage time, and must be populated efficiently. This includes processes involving the Xe*, like

\[X^* + X^* + \text{Products}\]

which must have a low probability for inelastic channels. This situation is most probable when only repulsive surfaces are present. All of the pulse energy must be stored in the laser upper level initially since there will be no pumping during the pulse. This last consideration favors an atomic transition rather than a molecular system, though molecular systems are not ruled out. There should also be a wide energy gap above any populated states of the lasing species before other energy levels or ionization limits are reached to avoid excited state absorption from the laser upper level. These, and other critical problems associated with the laser medium that must be considered, are given in Table II in a self-explanatory
Turning to possible atomic systems, large regions of the periodic table can be discarded immediately. Of those atoms remaining, the closest match to the desired properties are those atoms with partly filled p shells in which parity forbids allowed transitions between states of the lowest electron configuration, and in which 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 np$^2$ and np$^6$ configurations are found in carbon, oxygen, and higher members of the same columns of the periodic table, such as silicon, sulfur, germanium, and selenium.

The 1S-1D auroral line of atomic oxygen ($\lambda = 0.5577 \mu m$) has been analyzed as a model of this class of systems. Oxygen has been more carefully studied than the other atoms mentioned above, and much more information is available on its properties. The conclusions from this analysis are qualitatively applicable to the other atoms listed.

Efficient pumping of the laser upper level is required for the desired system. Since transitions from the atomic ground state to potential laser upper states are forbidden transitions 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 ground state to an excited molecular state which dissociates to give one of these atoms in the upper laser level, and these allowed pumping transitions appear to be the most practical means for pumping such a laser. The required pumping transitions lie at energies of perhaps 6 to 12 eV and can be excited either by electronic energy transfer in collisions or by absorption of photons. Electron beam excitation of gases, either directly in the lasers or in a scintillator for optical pumping of the laser, with, e.g., rare gas excimer radiation, is a very versatile technique for depositing large energies in high density gases on a short time scale.

Recent experimental and theoretical investigations of the rare gas excimer systems are directly applicable to both collision transfer and photolysis, since these systems can serve either as efficient fluorescers or as energy donors in selective collisional energy transfer processes.

4. A LASER SYSTEM CONCEPT

The 1S-1D auroral line oxygen laser model is carried a little further (assuming, of course, that it can be made to oscillate) in this section to illustrate the complexities of this class of lasers and anticipate some of the major systems problems involved. Assuming only 300° X Doppler broadening, the stimulated cross section, $\sigma(\nu_0)$, for the auroral line of atomic oxygen is $\approx 10^{-19}$ cm$^2$. Collision broadening will lower this somewhat so that a value of 7x10$^{-20}$ cm$^2$ may be more appropriate for practical amplifiers. Using this value for $\sigma(\nu_0)$ for the purpose of estimating the basic laser characteristics gives a transition saturation energy density of $\approx 5J/cm^2$, which is approximately a factor of two greater than the energy density limit of present mirror technology for 0.1 ns pulses at that wavelength. (Mirror technology should be able to safely handle this energy density, where LF systems become practical.)

Many reactions produce the 1S state of atomic oxygen. However, there is little information available from which to select the most efficient and least complicated process to produce the high excited state densities required for a compact laser design. The simplest and best understood source of O(1S) is the photolysis of simple molecules such as
CO₂, N₂O and O₂. Photolysis from N₂O absorption of continuum radiation near 0.1280 μm will be considered here, although other more suitable donors will most probably be found. The maximum efficiency of such a process is 23% while an input pump to output efficiency of ≈ 15% is more likely, considering realistic cavity pumping and extraction procedures.

Ar exhibits an excimer emission continuum that couples efficiently with the N₂O absorption continuum and is considered as a potential pump medium. However, energy losses during production of the photolysis radiation must also be considered. Ar is excited by radiolysis with a fast (≈ 1 Mev) electron beam with an efficiency estimated to be ≈ 30%. Presently these beams are produced by discharging a capacitor bank (Marks generator) through a pulse forming network (PFN) into a diode. Although the diode can be very efficient (90% assumed) the power conditioning equipment efficiency (ηPC) is presently very poor.

For the purposes of sizing a potential LF laser system based on the 1s-1D oxygen line, let us assume a modular concept where amplifier modules can be stacked to provide the 100 kJ pulse needed. The minimum module size might be expected to correspond with the output energy needed in each pellet irradiation arm. Working at the saturation flux level with a nominal 10 kJ module output, the required medium energy density is ≈ 30J/cm² with an inversion population density (Δn) of ≈ 10¹⁷ cm⁻³. The small signal gain of this cavity would be ≈ 0.7% cm⁻¹ [α₀ = Δnσ(ν₀)]. Under these conditions, a total gain of nearly 100 can be realized in 11 passes, each ≈ 1 m in length. Therefore, the required output could be achieved with a relatively small amplifier cavity with an input pulse of ≈ 100J. Cavity mirror sizes would range from ≈ 5-30 cm radius in the multipass system. Parasitic oscillations and superfluorescence may be a problem even with this small signal gain (Nc ≈ 8), so that care must be taken during an amplifier module final design.

Figure 3 shows an artist's sketch of a conceptual O(1S) laser module. Note that a gas synthesis unit is combined with a heat exchange unit after the amplifier section. N₂O must be regenerated after photolysis by an endothermic process which might be designed to use some of the waste heat energy from the laser (see g₆ in Figure 1). In this conceptual drawing the Ar is also flowed through the pump.

The laser system associated with a fusion power plant may be large and equally, if not more, complex than the reactor subsystem. In many concepts for irradiating the pellet, the laser is a separate entity, and high power beams are plumbed to the reactor through an evacuated optical transport system (Figure 4). In this arrangement the irradiation symmetry and timing required places stringent specifications on the optical path length (Δz might be as small as 0.1 cm) and pointing components so that thermal and mechanical stabilization will probably be necessary. (It appears desirable to keep the master oscillator and preamplifier as close to the reactor as possible.) As seen in Figure 4, a considerable problem exists in threading a laser beam through the other beams during the final approach to the reactor. This is particularly true if more than 12 beam irradiation symmetry is required. However, this arrangement also has several advantages. For example, low energy laser amplifier modules might be stacked in such a way to provide redundant operation in case of failure. Furthermore, unlike many military applications, space and weight are not critical so that the laser subsystem can be designed in an open configuration for ease of maintenance.

In another concept (Figure 5), three rings of four laser modules each surround the reactor. The blowers could be common to each gas ring or
placed in the ring, as shown. Although not shown in either configuration, gas composition and pressure control is required for efficient operation of the closed cycle lasers. From a reliability point of view, a common master oscillator providing the desired pulse shape, etc., appears attractive. In this case, only low power beams need be transported over a short distance to the amplifier. The final beam turning mirror placed in the Li blanket of the reactor must be self-healing (a liquid surface that reestablishes itself between pulses) or easily accessible for replacement. This mirror not only sees the laser pulse, but the particle and x-ray pulse from the pellet TN burn as well.

5. SUMMARY

The foregoing discussion characterizes some of the major problems associated with meeting the projected requirements for a laser system for LF. Foremost is the discovery of a suitable laser medium. The O\(^{1S}\) laser model type investigated might produce an overall system efficiency of \(\approx 4\%\) under the assumptions given. Referring to Figure 2 shows that this laser system would allow our reference design power plant to just reach breakeven - which is not a bad beginning for the early stage of LF research we are now experiencing. The laser model chosen necessarily contained both optimistic and pessimistic assumptions to an extent that in reality we do not yet know which way our estimated system efficiency will turn in the future. Also we know very little about optimized reactor designs and how we might short-circuit the plant power flow diagram using advanced concepts associated with waste heat recovery and laser pumping. For example, the reference plant output requirement \(C \approx 2.6\) might be achieved with a hypothetical O\(^{1S}\) laser \((\eta_L \approx 4\%)\) which obtains fast electrons to radiolyze Ar directly from TN burn neutrons or other debris\(^4\) with a 40% conversion efficiency. Of course, this may turn out to be impossible. Another potential route for lasers in power production is in fusion-fission hybrid systems where depleted uranium is used in blanket design.\(^2\) In a hybrid system, a circulating power index of \(C \approx 2.6\) can be reached with the same laser efficiency employing a blanket multiplication factor of \(m \approx 5\). If hybrid reactor concepts prove viable, they will have an important impact on the development of lasers for laser fusion. It is clear, however, that to achieve our goals in developing LF power our research must include such new concepts as part of a solid long-range program to find new laser media and improve the relevant system component technologies.
REFERENCES


7. "Laser Program at LASL", LA-5366-PR, Progress Reports.


<table>
<thead>
<tr>
<th>Spectral Region</th>
<th>Laser Medium</th>
<th>Wavelength (μm)</th>
<th>Medium Energy Density (J/μm²)</th>
<th>Efficiency (%)</th>
<th>Pulse Length (nsec)</th>
<th>Estimated Gain (Qn)</th>
<th>Laser System General Characteristics</th>
<th>Target Interaction General Characteristics</th>
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TABLE II
CRITICAL PROBLEM AREAS FOR LASER MEDIUM SELECTION

Optical Breakdown. The formation of a spark initiated by the intense optical field; the controlling parameters are the medium density, composition, and the optical wavelength.

Medium Density Gradients. Density gradients generate nonuniform refractive properties of the medium and cause an optical beam to diverge.

Self-focusing and Self Phase Modulation. These nonlinear electromagnetic propagation effects interfere with the amplification process.

Excited State Absorption. Absorptive processes (linear and nonlinear) originating from the upper laser level constitute an unwanted optical loss mechanism.

Parasitic Mode Suppression. Regenerative optical paths in the amplifier leads to an optical loss mechanism which limits the energy storage density.

Collisional Deactivation. In gaseous media, collisions of the active excited species with ambient atoms, molecules, and electrons lead to deactivation and loss of inversion density.

Pulse Distortion. Optical pulse spatial and temporal distortion arising from nonlinear propagation phenomena is a fundamental problem in the control of the optical energy.

Medium Energy Density. High energy storage density is desirable to achieve efficient and rapid transfer of pump energy and reduce optical component size.

Medium Saturation Flux. Should be close to optical component damage threshold for efficient energy extraction and system design.
Figure 1  Power Flow Diagram For A Reference Laser Fusion Power Plant
Figure 2 Plant Circulating Power Index As A Function Of Laser Efficiency
Figure 3  Laser Module - Conceptual Drawing For An O(^1 S) Type Medium
Figure 4 Separate Laser/Reactor System Concept
Figure 5 Integrated Laser/Reactor System Concept