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TITLE: DESIGN OPTIMIZATION OF SINGLE-MAIN-AMPLIFIER KrF LASER-FUSION SYSTEMS

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DESIGN OPTIMIZATION OF SINGLE-MAIN-AMPLIFIER KrF LASER-FUSION SYSTEMS

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ABSTRACT

KrF lasers appear to be a very promising laser fusion driver for commercial applications. The Large Amplifier Module for the Aurora Laser System at Los Alamos is the largest KrF laser in the world and is currently operating at 5 kJ with 10-15 kJ eventually expected. The next generation system is anticipated to be a single-main-amplifier system that generates approximately 100 kJ. This paper examines the cost and efficiency tradeoffs for a complete single-main-amplifier KrF laser fusion experimental facility. It has been found that a 7% efficient $310/joule complete laser-fusion system is possible by using large amplifier modules and high optical fluences.

INTRODUCTION

Considerable progress has been made on KrF lasers since they were first studied in 1974.[1] In 1975, they became one of many advanced short wavelength lasers being examined as potential drivers for inertial confinement fusion at Lawrence Livermore National Laboratory. A study of these potential drivers in 1978 concluded that e-beam pumped KrF lasers were quantitatively superior in efficiency to the other laser systems. This led to a series of articles and reports on solutions to the main problem associated with KrF laser-fusion systems: that they are not capable of energy storage and thus require laser pulse compression from the long pump times required for efficient laser energy extraction to the short target illumination time needed for high implosion efficiencies. Three pulse-compression methods originally received the most attention; Raman pulse compression, angular multiplexing, and a combined angular multiplexed and Raman compression system known as hybrid pulse compression.[4-6] During this same time period, the Department of Energy funded three in-depth studies to determine the characteristics of megajoule-class KrF lasers. Mathematical Sciences Northwest performed a conceptual design of a KrF scaling module using angular multiplexing (and existing technology) that could be scaled up in energy by replication.[7] Avco Everett Research Laboratory developed a conceptual design of a megajoule-sized angular multiplexed KrF laser with a repetition rate of 2-Hz.[8] Finally, Lawrence Livermore National Laboratory, Bechtel National, Physics International and Hughes Aircraft collaboration performed a study on a 1.5-MJ, 2-Hz KrF fusion laser system using Raman pulse compression.[9] The results of these studies were similar in that:

- estimated laser system costs were a few hundred dollars per joule,
- estimated laser system efficiency was between 3 and 4 percent, and
- technology development, especially in the areas of pulsed power, e-beams, and optics, was needed.

Recent advances have improved the outlook for KrF laser fusion drivers. The 1980 studies all used a gas mixture consisting of approximately 2-3 atmospheres argon diluent, 5-10% Kr and a trace of F_2, which resulted in a maximum intrinsic efficiency (defined as laser energy generated per unit pumping energy) of about 10%. New theoretical[10] and experimental[11] studies indicate that argon-free mixtures at approximately one atmosphere can result in intrinsic efficiencies as high as 17%. Improvements in the electron beam efficiency have also been realized through the use of segmented cathodes.[7,8] Segmented cathodes allow

- use of lower magnetic guide field which reduces the amplifier cost,
- shorter pulsed power rise times which increase the pulse power utilization, and
- higher pulsed power efficiency due to higher e-beam transmission through the hibachi by preventing emitted electrons from being intercepted by the major hibachi supports.

The combined improvements in pulsed power and intrinsic efficiency has resulted in estimated laser-system efficiencies more than double those of only five years ago.

Methods of reducing the cost of KrF fusion laser systems have also been addressed. Since a large fraction (30-50%) of the laser system cost is due to optics, this was easily recognized as a high-leverage area. Lightweight pressed and fused pyrex mirror blanks cost substantially less than conventional low-expansion glass. Planetary polishing also results in substantial cost savings over conventional polishing. Improvements in coatings allow higher operating fluences than just a few years ago, resulting in smaller (less expensive) optics.

The purpose of this paper is to re-explore the KrF scaling module in light of the recent advances. A baseline laser system concept will be described in some detail, and results of a system trade-off study will be presented to determine the characteristics of the optimal single-main-amplifier KrF laser-fusion system (with respect to cost and efficiency). A companion paper[12] to this one examines similar trade-offs for a multimodular MJ-class single-pulse KrF test facility.

LASER SYSTEM ARCHITECTURE

The laser system architecture used for this trade-off study is a modified version of the Aurora KrF laser under construction at Los Alamos National Laboratory, and is depicted in Figure 1. A 5-ns pulse generated in the front end undergoes aperture division, amplification in the small amplifier module, and intensity division. The beams are then angle encoded, sent through beam clean-up and into the first single-pass preamplifier. After exiting an optical relay, the beams are sent to the intermediate amplifier input array through a second single-pass amplifier. The beams are directed through the double-pass intermediate amplifier to an array used for directing the intermediate amplifier output into the main amplifier. Upon exiting the main amplifier, the beams are demultiplexed using two mirrors per beam and are sent to the target optics, which consists of two mirrors, a lens, and a window. The beams have now all reached the target simultaneously (or with the desired pulse shape).

There are additional components of the laser system besides the laser hardware. The high-power beams travel in beam enclosures with either helium or a soft vacuum used to reduce beam losses. A laser diagnostics and control system is used to fire the laser and to monitor its condition. An alignment system is used to maintain the proper beam and amplifier

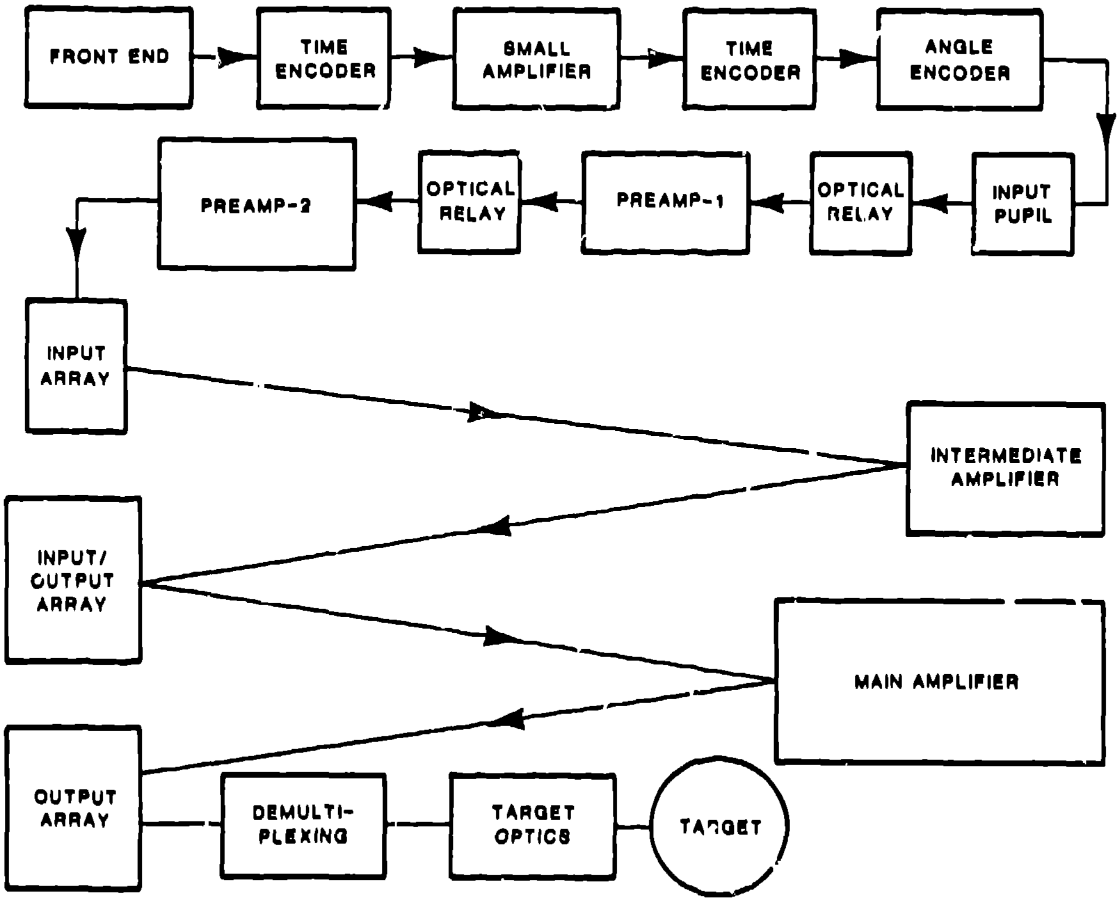

Fig. 1. Conceptual layout of the KrF laser system.

directions. A gas purification system maintains the correct gas mixture. Finally, a target chamber with a vacuum system and target positioning system is also included.

MODEL DESCRIPTION

A KrF laser system cost/performance model has been developed to perform trade-off studies for a complete inertial fusion experimental facility. The code uses present-day technology and costs with much of the information coming from the Aurora laser system and from conceptual design studies done for Los Alamos by Avco Everett Reserch Laboratory (AERL)[13] and TRW, Inc.[14] Los Alamos National Laboratory also has an ongoing design project with AERL for a 100 kJ laser amplifier using expanding flow (segmented) diodes. The trade-off study described here uses information from all of these sources in addition to input from Los Alamos personnel.

The computer code defaults define a baseline system which represents the starting point for the trade-off studies. This system uses 80 beams to illuminate a target with 100-kJ with shaped pulses constructed by superimposing 5-ns pulses. The main amplifier is pumped for 400-ns at 300 kW/cm^3 and is filled with 99.5% Kr and 0.5% F$_2$. The amplifier is pumped from two sides using 1.1 MV electrons through 5 diodes per side with a current density of approximately 30 A/cm^2. The main amplifier current rise time is calculated by the expression

$$\tau_{rise} = 2.2 \; \frac{L_{DIODE} + \dfrac{L_{BUSHING}}{N_{BUSHING}} + \dfrac{L_{SWITCH}}{N_{SWITCH}}}{Z_{LOAD} + Z_{PFL}} \; ,$$

where L is the inductance for the diode, bushing, and switch, Z is the impedence for the water lines and the load, and N is the number of buchings and switches. For the baseline system, the pulsed power utilization, defined as

$$\eta_{PPU} = \frac{\tau_{pump}}{\tau_{pump} + 0.04\,\tau_{rise}} \; ,$$

is 96%. The pulsed power efficiency is given by the product of five efficiencies: wall plug to high voltage (98%), high voltage to Marx generator (98%), Marx to pulse forming line (93%), pulse forming line to e-gun diode (95%), and e-gun diode to gas (70%). This gives an overall pulsed power efficiency of 59%.

The amplifier fill factor is calculated as a function of the amplifier dimensions and the distance from the input and output arrays to the amplifier. Using a separation length of 100-meters, the main amplifier fill factor is 98%. Coupling these efficiencies with 15% laser intrinsic efficiency, 95% beam transmission (from amplifier to target), 98% transmission through the amplifier window, and 97% transmission through unpumped regions containing fluorine give a total system efficiency of 7.6%.

In addition to all of the subsystems listed in the previous section, the code calculates costs for a power conditioning system, design, spares, contingency, and indirect field costs. The code calculates estimates for building costs but they are not included in the laser system cost. Figure 2 shows a breakdown of the laser system cost for the baseline system, which c[illegible]te $680/joule. Note that optics cost constitutes 33% of the total. Optics with more-damage-resistant coatings can be made smaller and can have substantial impact on the total laser system cost. This will be the first of many trade-offs examined in the following section.

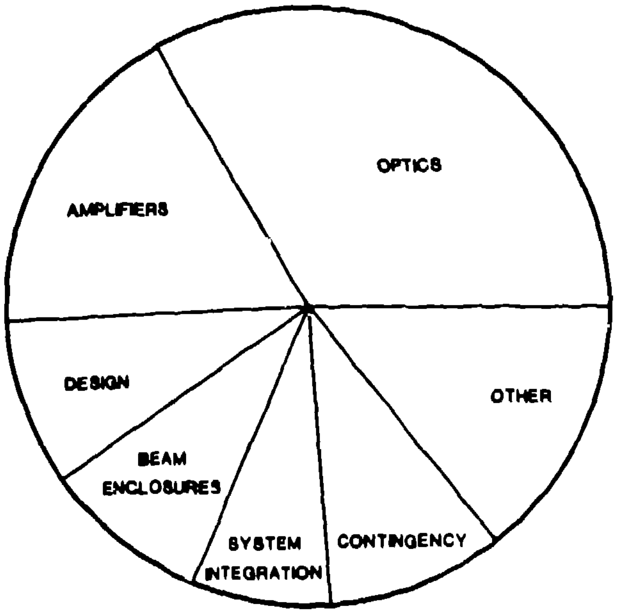

Fig. 2. Cost breakdown of the baseline 100 kJ laser system.

RESULTS OF TRADE-OFFS STUDY

A trade-off study has been performed in order to determine the optimal single-main-amplifier design in terms of cost and efficiency. Key parameters have been varied from the system baseline design to determine their sensitivity. Since optics represent the largest fraction of the baseline cost, the operating fluence was varied from the baseline value of 1.5 J/cm . As shown in Figure 3, increasing the fluence reduces the laser system cost, for both 100 kJ and 200 kJ systems. Since the larger system has a significantly lower cost per unit energy than the baseline system, the system energy scaling was examined next. Figure 4 clearly shows that the system unit cost decreases for larger systems with a slight penalty in efficiency. By combining large amplifier modules with high operating fluences, a 300 kJ system at 5 J/cm would cost $310/joule.

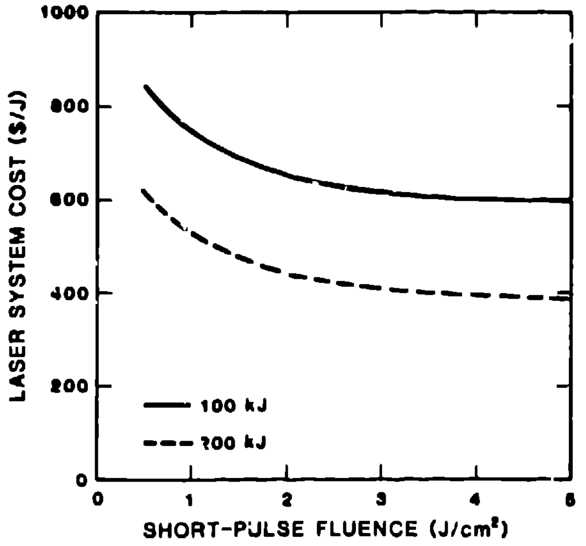

Fig. 3. Laser system cost as a function of the short-pulse fluence for 100 and 200 kJ laser systems.

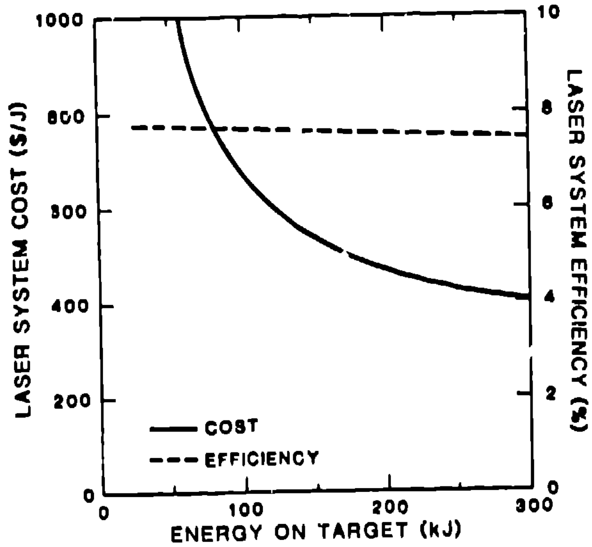

Fig. 4. Cost scaling and efficiency as functions of the energy on target.

Other trade-offs that have been examined have been found to be less significant. The laser pump duration sensitivity shown in Figure 5 has a broad minimum in cost near the baseline value of 400 ns. Shorter pump times result in lower system efficiencies due to lower pulse power utilization and higher costs due to larger pulsed power system. Longer pump times result in slightly higher costs due to large numbers of beam lines, and hence optical components and alignment stations. Figure 6 demonstrates that the amplifier window fluence does not significantly affect the cost, but does

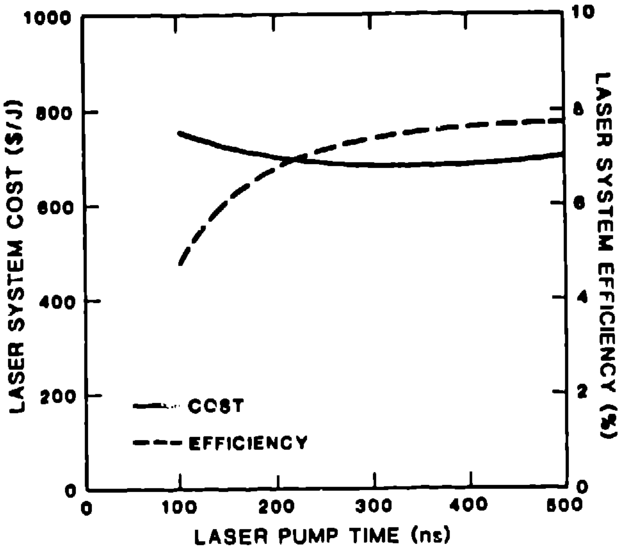

Fig. 5. Laser system cost and efficiency as a function of the laser amplifier pump time.

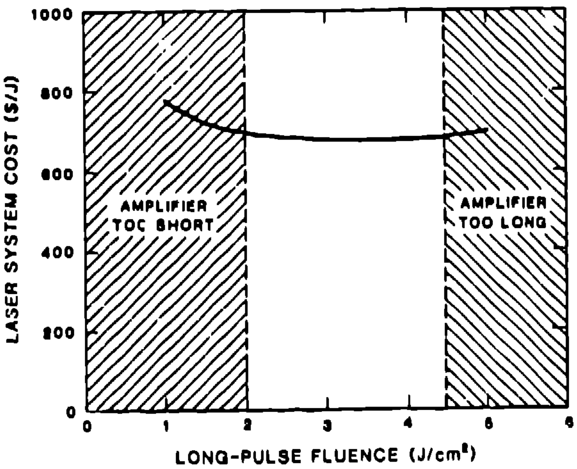

Fig. 6. Laser system cost as a function of the amplifier window fluence showing the region of acceptable aspect ratios.

affect the amplifier design. If only low fluences are allowed, the amplifier will be limited to lower energies in order to have reasonable aspect ratios; otherwise amplifiers will be too short. Higher fluences would result in too long of an amplifier which would result in lower fill factors. This would then allow larger energy amplifiers within the limits of amplified spontaneous emission, parasitics, and manufacturing limitations. Finally, Figure 7 shows the effect of varying the target illumination time. Very short times result in high costs due to the large number of small optical elements. Long illumination times have a slightly higher cost due to the small number of

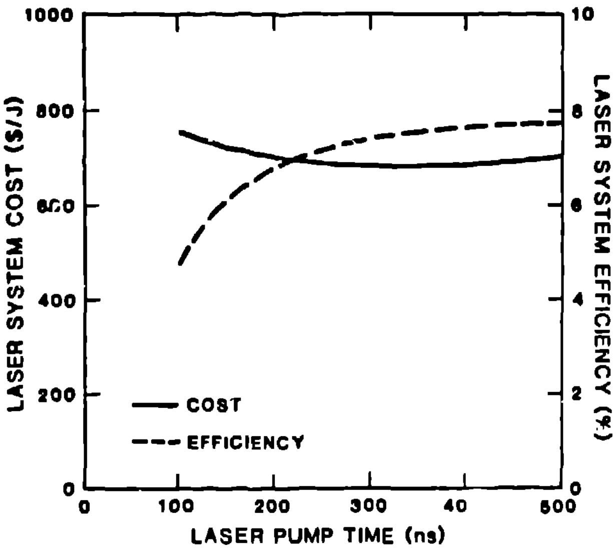

Fig. 7. Laser system cost as a function of the target illumination time.

large optical components. A broad minimum in cost occurs between 10 and 40 ns with a 10% cost penalty at 5 ns (the baseline case).

SUMMARY

Due to recent advances in KrF kinetics and e-gun diodes, KrF lasers look very promising as laser-fusion drivers. System efficiencies of 7-8% appear possible with today's technology. With costs of a few hundred dollars per joule, KrF lasers appear affordable for the next generation of experimental laser fusion facilities and are approaching cost/performance goals for commercial applications. Different trade-offs have been examined for a single-main-amplifier laser system. Large amplifier modules and high operating fluences have the greatest impact on the laser system cost, with a 300-kJ system operating at a fluence of 5 J/cm costing approximately $300/joule. Technology advances in optics, kinetics, and pulsed power expected in the near future and economies for larger systems can result in further unit cost reductions and improvements in efficiency.

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