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MEGAJOULE-CLASS SINGLE-PULSE KrF LASER TEST FACILITY AS A LOGICAL STEP TOWARD INERTIAL FUSION COMMERCIALIZATION

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ABSTRACT

The cost and efficiency of megajoule-class KrF laser single pulse test facilities have been examined. A baseline design is described which illuminates targets with 5 MJ with shaped 10-ns pulses. The system uses 24 main amplifiers and operates with an optics operating fluence of 4.0 J/cm^2. This system has 9.0% efficiency and costs \$200/joule. Tradeoff studies indicate that large amplifier modules and high fluences lead to the lowest laser system costs, but that only a 20% cost savings can be realized by going to amplifier modules larger than 200 kJ and/or fluences greater than 4 J/cm^2. The role of the megajoule-class single-pulse test facility towards inertial fusion commercialization will also be discussed.

INTRODUCTION

The requirements of a commercial applications inertial fusion driver have long been known. The driver must deliver 1-10 MJ with pulse widt[illegible]f 5-20 ns at a pulse repetition rate of 5-2[illegible] (for a 1000 MW plant), althoujh the optimum operating parametefs depend the cost and efficiency of the driver and the target gain.[1] The driver must also be efficient enough so that the product of the target gain and driver efficiency (ηG) be ≳10 for pure fusion power applications. Using standard target gain curves,[2] the driver efficiency should be at least 5-10 percent for laser drivers. The wavelength (for lasers) must also be less than 500 nm for efficient target coupling.[3] Only two lasers are thought to be scalable to the required energies with suitable wavelengths: frequency tripled Nd:ulass lasers and pulse compressed KrF lasers. KrF lasers have so far demonstrated higher system efficiencies and moreover, use a gaseous lasing medium that readily allows repetitive pulsing through convective heat removal. Previous studies[4] have concluded that e-beam-pumped KrF lasers have a maximum potential system[5] efficiency of 6 percent. Recent theoretical[6] and experimental work with a new regime of gas mixtures has indicated a possible 50% improvement in the laser intrinsic efficiency.[7] New work in expanding-flow e-beam diodes show improvements in the laser pumping efficiency. These effects combine to make KrF lasers an attractive commercial-applications laser fusion driver.

This paper examines the performance and cost scaling for megajoule-sized KrF laser fusion single-pulse test facilities (SPTF). A companion paper[8] describes the systems model used and similar tradeoffs for single-main-amplifier KrF laser-fusion systems. This model is used here to calculate the cost of larger single-pulse systems. A second companion paper[9] describes KrF laser cost and efficiency scaling for commercial-applications repetitively pulsed systems.

THE SPTF AND THE ICF COMMERCIALIZATION PLAN

The successful development of commercial applications inertial fusion (including production of electric power, fissile fuel, special nuclear materials, and process heat) depends[10] upon the following essential activities:

- high-average-power (high pulse energy/repetition rate) driver development,
- high target gain,
- commercial target manufacturing,
- materials development,
- reactor system development,
- fuel cycle development, and
- total system integration.

Driver development begins with small systems to test performance expectations and to benchmark modeling codes. The next step is to scale the driver up in energy. KrF laser development is currently in this stage. After several laboratories have built sub-kilojoule-sized lasers, the large amplifier module at Los Alamos National Laboratory has recently demonstrated 5 kJ, with 15-20 kJ eventually expected. A 100-kJ amplifier called the power amplifier module (PAM) is currently being designed in a cooperative Los Alamos/Avco Everett Research Laboratory effort. The PAM will be used to study main amplifier scaling and to explore design options (new optics concepts, lasing media mixes, e-beam diode and pulsed

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED [illegible] designs, etc.) that promise cost and efficiency improvements. Some promising alternative concepts can also be investigated using the same facility. The next logical facility built for driver development would be the megajoule-class single-pulse test facility (SPTF). This system would demonstrate multimodular integration and would also be used for the development of high gain targets. The purpose of this paper is to describe the cost and performance of a 5-MJ SPTF. The SPTF could be similar to the commercial-applications driver with the exception of repetitive pulsing (which could be an upgrade option).

An engineering test facility (ETF) would be required after the SPTF. The ETF would be a small scale system (≤ 1 MJ) that would demonstrate repetitive pulsing, target injection and tracking, and system integration. This facility would require commercial target manufacturing and would be able to perform materials and reactor system development. A demonstration plant (DP) would be the next logical step. The DP would be required to prove reliable and economic operation, and might be in the form of a hybrid or a fissile fuel breeder to ease target and driver performance requirements. The remainder of this paper will describe the megajoule class SPTF, which is the next major facility to be built after the 100 kJ PAM at Los Alamos.

DESCRIPTION OF THE BASELINE SPTF

The baseline approach uses large electron-beam pumped double pass amplifiers pumped for 400 ns for high efficiency. Many angularly multiplexed beamlets, generated from a single front end pulse, are passed through single-pass preamplifiers and intermediate amplifiers, split, and sent to a small double-pass amplifier before entering the main amplifier. The beamlets emerging from the main amplifiers are then superimposed on the target with the beam delay timing adjusted to produce the proper pulse shape and duration on the target. The baseline SPTF illuminates targets with 5 MJ in variable-shape pulses with widths ≥ 5 ns.

The baseline design uses 24 main amplifiers that are 2.3 meters high and wide, and 2.8 meters long. The amplifiers are arranged in a linear array and use beam combination via turning mirrors located in front of the amplifier window (see Figure 1). After leaving the main amplifier output array, each beamlet uses two mirrors for demultiplexing, and two mirrors, a lens and a window for target optics. The operating fluence is 4.0 J/cm^2.

The overall system efficiency for the baseline design is 9.1% from wall plug to energy on target. The main amplifier intrinsic efficiency is 14.6%, with 75% pulsed power efficiency and 94.2% pulsed power utilization (accounting for pulsed power rise and fall times). Approximately 3% of the laser energy is lost in the unpumped regions containing F_2 near

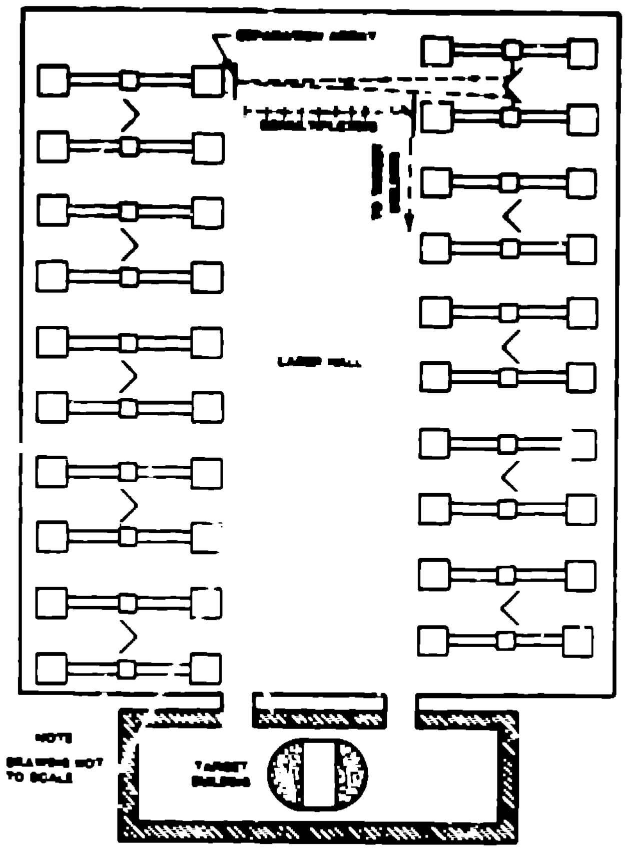

Fig. 1. Conceptual layout of a 5 MJ SPTF using 24 amplifiers. Beam combination is performed using large mirrors between pairs of amplifiers.

the amplifier window, and 2% is lost in the window itself. The main amplifier fill factor is 97.4%, and 5% laser energy loss is assumed for the beam transport to target.

The baseline system cost is approximately \$200/joule for the laser system, and \$205/joule for the entire facility including the laser hall, an office building, and a well-shielded target building. For this system, 40% of the cost is due to optics and mounts, 16% is from laser amplifiers, 14% is from beam enclosures, and 9% is design costs. The remaining 21% is associated with spares, contingency, indirect costs, power conditioning, a gas purification and handling system, the target chamber, alignment, controls and diagnostics systems, system integration, and the front end.

SPTF SYSTEM TRADEOFFS

The results of a system tradeoff study around a 5-MJ SPTF show similar trends as for the single-main-amplifier study.[8] Figure 2 shows the laser system cost scaling as the energy on target increases up to 10 MJ for nominal 100, 200, and 300 kJ amplifier modules. This figure shows that large systems and large

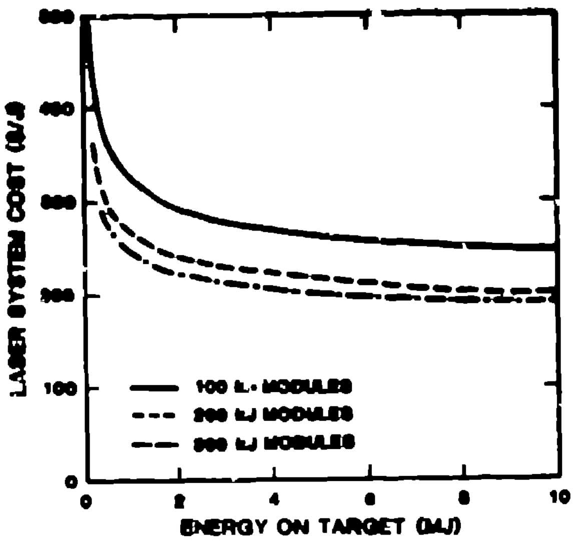

Fig. 2. Laser system cost scaling as a function of energy on target for three amplifier module sizes.

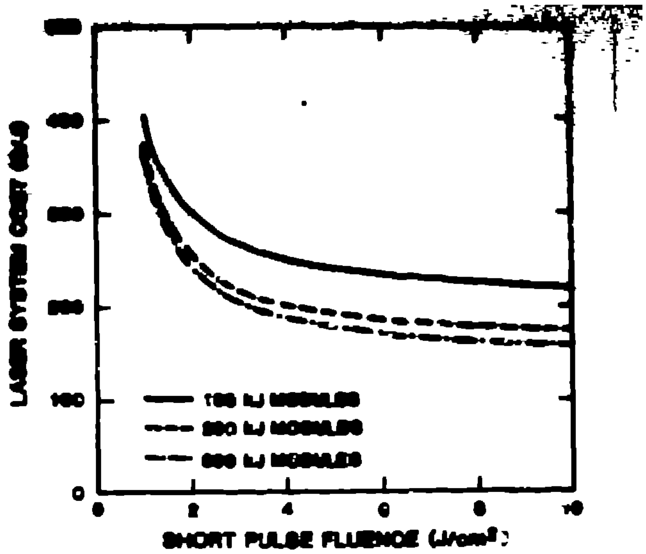

Fig. 3. Large optical fluences and large amplifier modules lead to the lowest system cost for the 5-MJ SPTF.

amplifier modules result in lower unit cost. Figure 3 shows the effect of the short pulse fluence on the laser system cost for the 5-MJ system using the same three different sizes of amplifiers. As expected, large optical fluences result in lower costs. A somewhat unexpected result is that increasing the fluence from 4 J/cm^2 to 10 J/cm^2 only decreases the total laser system cost by 10%. This is encouraging because most of the cost reduction is possible in the low fluence end, in the range of expected advances in coating technology.

The only other tradeoff examined that showed a significant cost sensitivity was the target illumination time. As shown in Figure 4, short target illumination times result in much higher costs. This is due to the large number of small optical components used in the system. The system cost has a broad minimum over the intermediate range of illumination times. There is a slight increase at long illumination times because of the large optical components (though small in number) needed in the system. If KrF lasers prove to be the best commercial applications inertial fusion driver, it may be important to develop targets that are optimized for peak power illumination times $\gtrsim$ 6 ns.

SUMMARY

This paper has examined the role of a single-pulse test facility with respect to the goal of commercial applications inertial fusion. A 5-MJ KrF laser system baseline design has been costed in detail, and tradeoff studies were performed to examine the effects that variations in principal design parameters have on the laser system cost and performance. We found that the baseline laser system cost is ~200/joule and the system efficiency is ~9%. The results of the tradeoff study indicate that large optical fluences and large amplifier modules are cost effective, but only a 20% cost savings over the baseline design can be realized by going to larger fluences and/or larger amplifier modules. Therefore, 200-kJ modules and 4 J/cm^2 operating fluences are all that are needed to produce an affordable system.

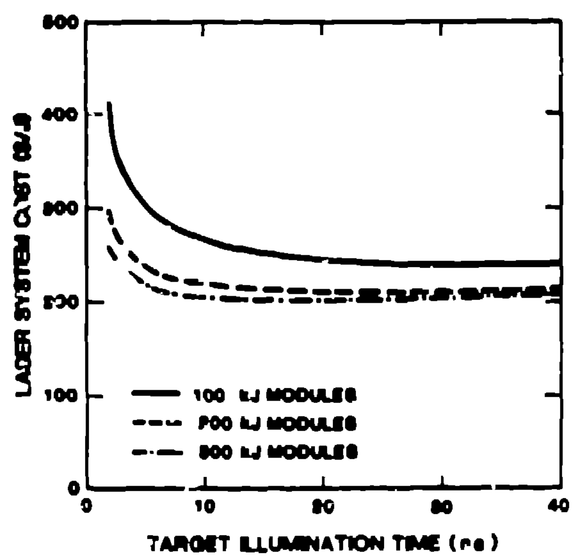

Fig. 4. Short target illumination times drive the laser system cost up. For large amplifier modules, a broad cost minimum exists between 8 and 40 ns.

It should also be noted that the tradeoff study was performed in a simplistic manner in that the system was not reoptimized each time.

[illegible], very short illumination times lead to high system costs due the large number of [illegible] optical components. One way to improve [illegible] is to aperture combine more than two amplifiers per optical component. This technique would also be useful for smaller amplifier modules. Future studies will examine these optimized systems in more detail. Also, alternative KrF laser concepts that have potential for even higher efficiencies and lower costs are under investigation.

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