A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

1

LA-UR -89-2205

CONF-890711--1

Received by OSTI

1989

LA-UR--89-2205

DE89 014272

TITLE KrF LASERS FOR INERTIAL CONFINEMENT FUSION

AUTHOR(S) D. B. Harris, D. C. Cartwright, J. F. Figueira, T. E. McDonald, M. E. Sorem

SUBMITTED TO 5th Int'l Conf.on Emerging Nuclear Energy Systems,
Karlsruhe, FRG
July 3-6, 1989

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

FORM NO. 836 R4
ST. NO. 2629 5/81

KrF LASERS FOR INERTIAL CONFINEMENT FUSION

David B. Harris, David C. Cartwright, Joseph F. Figueira,
Thomas E. McDonald, and Michael E. Sorem
Los Alamos National Laboratory
Los Alamos, New Mexico 87545 USA

ABSTRACT

The KrF laser has been proposed for inertial confinement fusion (ICF) since its discovery in 1975. Since that time, the laser has seen significant development and has been increased in energy many orders of magnitude to the several kilojoule energy level. The suitability of the KrF laser as a driver for ICF energy applications has been continually reviewed. The latest assessments indicate that the KrF laser still appears to be the leading laser candidate. A worldwide effort exists to advance the KrF laser for ICF applications.

I. INTRODUCTION

The inertial confinement fusion (ICF) process begins with a laser or particle beam depositing energy in the outer layer of a fuel capsule. This outer layer heats up and expands, causing the inside of the fuel capsule to compress or implode via conservation of momentum. If the implosion velocity of the fuel is both symmetric and high enough, the deuterium-tritium fuel can achieve the high densities and temperatures needed for a significant number of fusion reactions to occur. The *inertia* of the imploded fuel provides the confinement time needed for high fuel burnup. If the fuel mass is great enough, requiring driver energies in the megajoule regime, the fusion yield can be much higher than the driver energy, and significant energy gain can be achieved Finally, with a high efficiency driver, the fusion energy can be higher than the driver "wall-plug" energy, and useful energy production is now possible.

The KrF laser has been proposed as an ICF laser driver since its discovery in 1975 [1] because of its natural properties. This paper will examine how well the KrF laser characteristics fit with the requirements for ICF as they are currently known. It must be stated that the ICF requirements for high gain are not currently known with great accuracy or confidence; only after an ICF facility reaches the ignition/breakeven regime can these parameters be accurately specified.

There are two key target physics issues in the ICF process:

1. How much energy absorbed in the ablator, E_a, is required for high gain?
2. How much driver energy, and with what characteristics (wavelength, bandwidth, pulse shape, beam quality, etc.), is needed to provide E_a?

The status of these issues and the relevant characteristics will be discussed in Section II.

The U. S. ICF program has taken the approach to resolve target physics issues with single-pulse drivers. After these issues are resolved, repetitively pulsed lasers would be developed for commercial applications. The specific path proposed by Los Alamos and development progress for KrF lasers will be examined in Section III.

Section IV will examine the current status of the KrF laser-fusion program at Los Alamos. This will include the Aurora laser system which as recently begun to perform target experiments and the Los Alamos KrF technology development program. In addition, we will also review the status of major KrF laser facilities around the world.

Finally, Section V will briefly discuss some the non-laser issues that need to be resolved before the realization of ICF commercial applications such as electric power production. This includes target fabrication; target injection, tracking, and driver pointing; and ICF reactor vessels.

II. REQUIREMENTS FOR ICF COMMERCIAL APPLICATIONS DRIVERS

An ICF driver for commercial applications must satisfy several requirements: low cost, high efficiency, moderate repetition rates, high reliability, and good target coupling [2]. There are very few "cliffs" in performance--a driver that has lower target coupling or lower efficiency can make up for it with lower cost, and vice versa. The requirements presented here are basic guidelines or rules of thumb and should not be taken as strict requirements

The requirements can be divided into two categories with target coupling being in a category by itself. The reason for this is that target coupling can be fully addressed on single-pulse test facilities. We will discuss the driver requirements first and then discuss target coupling. Additionally, there are several types of commercial applications that have been considered, including production of electric power, process heat, and fissile fuel. In this paper, we will consider only electric power production. Electric power production using ICF probably has the most rigorous requirements of all of the commercial applications. If this turns out to be unattractive for economic reasons, other applications may still be possible.

II.A. Driver Requirements

As mentioned before, the driver must have low cost and high efficiency to have a low cost of electricity. The cost of electricity as a function of driver cost and efficiency can be calculated using simple assumptions for the cost of targets, reactors, and balance of plant [3,4]. In general, a reasonable goal is a cost of less than ~\$300/joule and an efficiency of greater than ~5%. The efficiency requirements depend strongly on target gain, which has large uncertainty at this time. The real requirement is the the product of the driver efficiency and target gain be greater than ~8. This translates to the balance of plant required just to provide electricity for the driver being less than ~25% of the total balance of plant required.

The driver must be able to operate at an repetition rate in the range of 1-10 Hz to operate with an affordable cost of electricity [3,4]. Below 1 Hz requires a large driver energy (for a 1000 MWe power plant) operating with very high gain and yield per shot. and above 10 Hz probably has too high of a target cost for an acceptable cost of electricity [3-5].

Perhaps the most difficult requirement to estimate that needs to be satisfied is the driver reliability. For electric power production, the driver must operate for the best part of a year without major shutdown or malfunction. At 5 Hz and an availability of 70%, the driver must be fired $\sim 10^8$ times per year. Estimating the cost of and constructing the reliability of the driver for this many shots per year (with a 30 year lifetime?) will be difficult.

Projections of the KrF laser appear to be able to satisfy these requirements [2,3]. Being a gas laser, it is relatively straightforward to satisfy the repetition rate requirements: removal of the laser waste heat is accomplished by flowing the heated laser gas through a conventional heat exchanger [6,7]. Two key issues are the development of a reliable, repetitive pulsed power system for the KrF laser and the uniformity of the gas in the amplifier using a flow system. Both issues appear solvable. Several possibilities for the pulsed power system have been identified [6]. Gas flow issues have been examined in detail both experimentally [8] and theoretically [9], and the required gas uniformity appears feasible.

The efficiency of an ICF commercial applications KrF laser should be high enough for an attractive cost of electricity, especially with the credit for using the laser waste heat for feedwater preheat [10]. Projections indicate that the cost of the KrF laser can be made affordable, but much development is required. KrF laser development is the subject of section IV. Finally, the reliability of the KrF laser must match the ICF commercial applications requirements. Again, this will take much development and further, is not currently in the focus of the U.S. ICF program goal of demonstrating high gain ICF targets using single-pulse drivers. Therefore, little effort is being placed in improving the reliability of KrF lasers to the degree needed at this time.

II.B. Target Coupling

The main emphasis of the U.S. ICF program is to accurately determine the driver energy and characteristics required for high target gain. The focus of the U.S. ICF program is a facility called the Laboratory Microfusion Facility (LMF) [11]. One of the goals of the LMF is to demonstrate high target gain, which will verify the *scientific* feasibility of ICF commercial applications. There is a long way to go to demonstrate the *engineering* feasibility of ICF commercial applications for the reasons described in sections II.A. and V.

The target coupling is simply a measure of comparison of a set of driver characteristics to the target yield for a given driver energy. Good target coupling means that the driver energy couples efficiently to the target and thus the yield is high. Poor target coupling results in poor target performance.

For lasers, target coupling is generally thought of in terms of the following four parameters:

- wavelength--must be short enough to not generate a significant number of fast electrons which degrade the implosion [12],
- bandwidth--is desired to be broad to inhibit the growth of instabilities which degrade the implosion [13-14],
- pulse shaping--accurate pulse shaping has long been known to significantly increase the target yield [15], and
- beam quality--needed to smoothly focus the laser light from the long distance required for final optics protection from the target output.

The KrF laser appears to be the optimum laser in satisfying the target coupling requirements [2]. The wavelength is near-optimum for absorption by the target without degradation from fast electrons [12]. The bandwidth is sufficiently broad to reduce instability thresholds and growth rates. Accurate pulse shaping is possible because the gain of the laser is linear, allowing the desired pulse shape to be generated in the front end and propagated through the amplifier chain to the target without distortion [16]. In addition, because the laser operates naturally at a short wavelength, there is no need for inefficient, intensity dependent frequency multiplying crystals that significantly distort the pulse shape and degrade the beam quality. Finally, because the KrF laser uses a self-healing gaseous lasing medium, the beam quality can be very good, allowing focusing to small spots from long distances. In addition, the KrF laser is suitable for beam smoothing by using a technique called Induced Spatial Incoherence (ISI) [17].

III. DEVELOPMENT PATH FOR KrF LASERS

Willke has published a logical path for the development of ICF commercial applications [18]. This path first demonstrates high target gain on single-pulse facilities. This verifies the scientific feasibility of ICF *before* the difficult task of developing repetitively pulsed drivers with high efficiency, low cost, and high reliability. The U.S. is currently following this path to commercial applications. It should be noted that the plan begins with a facility to demonstrate high gain, which is still a significant way off. In the U. S., the high-gain test facility is currently being examined in the Laboratory Microfusion Facility Scoping Study [11].

Current ICF drivers are not capable of demonstrating high gain. Major issues on capsule performance and driver-target coupling create large uncertainties in the driver energy, pulse shape, etc., needed for high gain. Additionally, driver cost has not been demonstrated to be affordable while delivering the desired drive conditions to the target. Because of these uncertainties, Los Alamos has proposed a lower-energy, lower-cost prototypical facility that will resolve these target issues and demonstrate driver cost and performance. This facility has not received funding at this time.

IV. STATUS OF KrF LASER-FUSION DEVELOPMENT

The most advanced KrF laser-fusion system is AURORA [19], located at Los Alamos. As illustrated in Figure 1, AURORA is a 5-8 kJ, 2-5 ns pure angular multiplexed system. AURORA was designed to demonstrate all of the key elements of an electron-beam-pumped, angular multiplexed KrF laser. AURORA fired its first full system shot in December 1988 and achieved ~2.5 kJ out of the main amplifier.

KrF lasers are also being developed around the world. Sprite was the first of the existing KrF laser systems to come on line. Sprite is a 100-kJ-class KrF laser located at Rutherford Appleton Laboratory in the United Kingdom. The Ashura laser at the University of Osaka is a kilojoule-class KrF laser currently performing experiments. The University of Alberta has a kilojoule-class laser currently under construction, as is the Nike system at the Naval Research Laboratory in Washington, DC. The main thrust of Nike is to demonstrate beam smoothing by ISI.

Los Alamos has been performing design studies of the next generations of KrF laser-fusion systems for several years. We have been participating in the Laboratory Microfusion Facility Scoping Study and are currently completing the conceptual design of a 10-MJ KrF laser-fusion facility. A more near-term design of a 100-kJ facility driven by two 50-kJ KrF amplifier modules is also being completed.

These design studies have been extremely important in determining the high-cost-leverage elements of the designs. Results have indicated that the cost of amplifiers and optics dominate the driver cost estimate. Los Alamos has instigated technology development programs to reduce the cost of these items. In particular, the optics development program is aimed at increasing the optical damage threshold at 248 nm and in reducing the cost of optical components through improved manufacturing technology. The cost impact of amplifiers can be reduced by scaling them to larger sizes and increasing the efficiency of the laser module. This is the goal of the amplifier technology development program at Los Alamos. While these programs are aimed at lowering the cost of single-pulse KrF laser-fusion systems, the work is equally applicable to repetitively pulsed reactor drivers.

V. NONDRIVER ISSUES FOR ICF COMMERCIAL APPLICATIONS

There are an additional set of issues that need to be resolved in order to realize ICF commercial applications. In fact, it has been estimated that the driver-independent issues are much more significant than the issues involved with developing the KrF laser into a reactor driver. Leading the list of the driver independent issues is the development of a reactor vessel. Many concepts have been proposed [20,21], and all have significant issues and uncertainties associated with them.

Target manufacturing is another issues involved with the development of ICF commercial applications. Today's targets are currently made, filled, mounted, and characterized with great expense and time. Targets for an electric power plant must be made with a great deal of remote equipment at the same rate as the repetition rate of the driver. This has been examined in some detail [5], and cost projections have been made that appear attractive for electric power production. However, realization of this technology will require significant development.

Another target-related issue is the injection of the target into the reactor. Current target designs use cryogenic fuel to begin the implosion on a low adiabat and achieve a higher compression. This frozen D-T capsule must remain in that state as it is injected into the reactor, which will undoubtably be at a high temperature. Related to the target injection issue is the requirement for tracking and pointing of the driver beams to strike the target simultaneously. Tracking of a small cold object in a hot background will require development.

Finally, for laser drivers, the final optics will be in the direct "shine" of the target output, which includes neutrons, x rays, target debris, and high-energy charged particles. In order for the optics to survive for a reasonable time, they must be protected. Current schemes include gas protection for x rays and charged particles, magnetic fields for the charged particles and target debris, and distance for the neutrons. Final optics survivability is a area that will require development for ICF commercial applications to be realized.

VI. CONCLUSIONS

The KrF laser has undergone significant development since the discovery in 1975. Work is being done worldwide to further understand ICF target issues and the KrF laser. The KrF laser currently appears to be the most attractive driver for ICF commercial applications, mainly because of the near-optimum target coupling, the gaseous lasing medium, and the high efficiency offered by the electron-beam-pumped excimer laser.

At Los Alamos, we are following the path of demonstration of the scientific feasibility first before development of a reactor driver. The goal at Los Alamos is to demonstrate high target gain with a single-pulse driver. Conceptual designs of future systems have been completed and the high-cost-leverage items have been identified. Los Alamos has technology development programs designed to reduce the cost and/or increase the reliability and performance of KrF lasers.

Though these studies have maintained the feasibility of KrF lasers for commercial applications, there is much development required. The KrF laser must develop repetitive pulsing, which requires development in the areas of pulsed power and gas flow. ICF power plants have the added issues of target manufacturing, injection, tracking, and driver pointing. Finally, ICF reactors must be developed that can contain the microexplosions and convert the fusion energy to heat while protecting the final optics.

REFERENCES

1. J. J. Ewing and C. A. Brau, "Lasing Action on the Bands of KrF and XeCl," Applied Physics Letters, 27, 350 (1975).

2. D. B. Harris, L. A. Rosocha, and D. C. Cartwright, "Los Alamos National Laboratory View of Commercial Drivers for Laser-Driven Reactors," Proceedings of the Third Inertial Confinement Fusion Systems and Applications Colloquium, University of Wisconsin-Madison report UWFDM-749, (1988).

3. D. B. Harris et al., "Future Developments and Applications of KrF Laser-Fusion Systems," Fusion Technology, 11, 705 (1987).

4. D. B. Harris, "KrF Laser-Fusion Power Plant Cost of Electricity Sensitivity to Target Cost and Gain," Bulletin of the American Physical Society, 31, 1411 (1986). Also Los Alamos National Laboratory report LA-UR-86-3559 (1986).

5. J. H. Pendergrass, D. B. Harris, and D. J. Dudziak, "Heavy-Ion Fusion Target Cost Model," Fusion Technology, 13, 375 (1988).

6. L. M. Waganer, D. S. Zuckerman, and D. A. Bowers, "KrF Laser System Studies," McDonnell Douglas Astronautics Company final report (1986).

7. D. B. Harris, L. M. Waganer, D. S. Zuckerman, and D. A. Bowers, "Conceptual Design of a Large Electron-Beam-Pumped KrF Laser for ICF

Commercial Applications," Transactions of the American Nuclear Society. 52, 146 (1986).

8. P. M. Hurdle, J. H. Morris, S. C. Crow, and H. D. Hogge, "Experimental Investigation of Flow and Acoustics in Pulsed Excimer Lasers," Poseidon Research report 22 (June, 1979).

9. H. D. Hogge, S. C. Crow, J. H. Morris, and P. M. Hurdle, "Modeling and Simulation of Flow and Acoustics in Pulsed Excimer Lasers," Poseidon Research report 21 (February, 1979).

10. J. H. Pendergrass, "Improving Inertial Confinement Fusion Power Plant and Effective Driver Efficiencies by Generating Electricity from KrF Laser Reject Heat," Fusion Technology, 11, 732 (1987).

11. "LMF Laboratory Microfusion Capability Study Phase I Summary," U.S. Department of Energy report DOE/DP-0069 (1989).

12. K. A. Brueckner and R. S. Janda, "Wavelength Dependence of Laser Coupling to Pellet Implosions," Nuclear Fusion, 17, 305 (1977).

13. D. W. Forslund, J. M. Kindel, and E. L. Lindman, "Plasma Simulation Studies of Stimulated Scattering Processes in Laser-Irradiated Plasmas," Physics of Fluids, 18, 1017 (1975).

14. K. Estabrook, W. L. Kruer, and B. F. Lasinski, "Heating by Raman Backscatter and Forward Scatter," Physical Review Letters, 45, 1399 (1980).

15. J. Nuckolls, L. Wood, A. Thiessen, and G. Zimmerman, "Laser Compression of Matter to Super-High Densities: Thermonuclear (CTR) Applications," Nature, 239, 139 (1972).

16. D. Hanson and J. Ackerhalt, "Pulse Shaping and KrF as a Storage Laser: Consequences for Aurora," Los Alamos National Laboratory memorandum T-12(87)DH32 (1987).

17. R. H. Lehmberg and J. Goldhar, "Use of Incoherence to Produce Smooth and Controllable Irradiation Profiles with KrF Fusion Lasers," Fusion Technology, 11, 532 (1987).

18. T. Willke et al., "A Plan for the Development and Commercialization of Inertial Confinement Fusion," Argonne National Laboratory report ANL-79-41 (1979).

19. L. A. Rosocha et al., "Aurora Multikilojoule KrF Laser System Prototype for Inertial Confinement Fusion," Fusion Technology, 11, 497 (1987).

20. M. J. Monsler, J. Hovingh, D. L. Cook, T. G. Frank, and G. A. Moses, "An Overview of Inertial Fusion Reactor Design," Nuclear Technology/Fusion, 1, 3, 302 (1981).

21. W. J. Hogan and G. L. Kulcinski, "Advances in ICF Power Reactor Design," Fusion Technology, 8, 2A, 717 (1985).

FIGURE CAPTIONS

Figure 1. Aurora is leading the state of the art in KrF laser-fusion systems. The unique configuration of Aurora is due to using an existing building to house the laser amplifiers. Beam enclosures were added to transport the beams to target.

AURORA: THE LOS ALAMOS SHORT-PULSE MULTI-KILOJOULE ANGULAR MULTIPLEXED KrF INERTIAL FUSION LASER SYSTEM