LA-UR -80-2907

TITLE: THE STATUS OF LASER DRIVERS FOR INERTIAL CONFINEMENT FUSION

MASTER

AUTHOR(S): Eugene E. Stark, Jr.

SUBMITTED TO: 4th American Nuclear Society Topical Meeting
on the Technology of Controlled Fusion,
King of Prussia, PA, October 14-17, 1980

University of California

LOS ALAMOS SCIENTIFIC LABORATORY
Post Office Box 1663 Los Alamos, New Mexico 87545
An Affirmative Action/Equal Opportunity Employer

Form No. 836 R3
St. No. 2629
12/78

UNITED STATES
DEPARTMENT OF ENERGY
CONTRACT W-7405-ENG. 36

THE STATUS OF LASER DRIVERS FOR INERTIAL CONFINEMENT FUSION

by

Eugene E. Stark, Jr.

Los Alamos Scientific Laboratory*
Los Alamos, New Mexico 87545

ABSTRACT

The requirements and primary tradeoffs on laser drivers for ICF are discussed. The status of drivers, technology requirements and projections of future are discussed.

I. INTRODUCTION

Although the greatest uncertainty in the feasibility of Intetial Confinement Fusion involves the possibility of designing high-gain pellets, the demanding requirements on driver performance are also indispensable to ICF. The present understanding of these requirements is given in Table 1.

Pulse energy, length and repetition rate requirements have wide ranges because of uncertainties in the design of high-gain pellets and in the technology and economics of inertial fusion reactors the prepulse energy limit is imposed by the need to avoid preheating the pellet before the major laser pulse arrives. To permit the laser pulse to focus strongly onto the pellet, the reactor chamber pressure must be limited (to avoid laser gas-breakdown) and this necessitates a pressure interface between the laser and the chamber. The product (η) of driver efficiency and pellet gain (fusion energy output laser energy input) is determined by systems studies and economic

---

*Work performed under the auspices of the United States Department of Energy

TABLE I

LASER SYSTEM REQUIREMENTS FOR ICF

Pulse Energy	2 - 5 MJ
Pulse Length	1 - 10 ns
Repetition Rate	1 - 40 Hz
Efficiency-Pellet Gain Product	2 (fusion-fission) 10 (pure fusion)
Efficiency	> 5Δ
Beam Focusability	to 1mm
Pressure Interface	to 0.1 torr in reactor chamber
Prepulse Energy	10 mJ
Time Between Major Shutdowns	1 year

considerations of recirculating power requirements. The efficiency requirement is not absolute, but is highly desirable based on predictions of the variation of electric power costs with driver efficiency.

The primary tradeoff issues involve vs. Q, capital cost versus efficiency the relative advantages of the laser wavelength, and design issues of capital versus operating costs and reliability. Because there may be a limit to the acceptable microexplosion energy release in an ICF reactor, there may be a limit on the acceptable pellet gain Q, so that absolute laser efficiency may be an important factor. Laser systems typically have a strong tradeoff between system cost and efficiency, so that this is an important issue in system design. Wavelength issues will not be discussed in detail in this paper, but it should be noted that relative performance in driving pellets is indeed a tradeoff issue which must be weighed against drive efficiency, cost and reliability. Cost/reliability issues have not been studied in detail for laser drivers and will not be discussed further.

The major candidate lasers today are CO_2 and KrF; their status, projections and technology are the primary subject of this paper. This information builds upon a previous related discussion.[1]

II. THE CARBON DIOXIDE LASER

The CO_2 laser is a molecular laser containing nitrogen, carbon dioxide and sometimes helium. An electric discharge excites vibrations in the nitrogen molecules, which then transfer their excitation to the CO_2, thereby creating a molecular level population inversion and hence optical gain. Because the excited nitrogen molecules have no dipole-allowed transitions, their excitation is long-lived, and so the CO_2 laser has an intrinsic (maximum theoretical) efficiency of 40%, with 30% demonstrated in ?s-scale operation. Repetition rates of several hundred Hz have been demonstrated.

The status of the CO_2 laser is best illustrated by the Helios laser at Los Alamos. In Helios, eight electric discharge regions, driven by a short-pulse laser front end, produce a total of 10 KJ of energy at the 10.6?m wavelength, in a 1ns pulse with an efficiency of 2%. The operational parameters of the Helios amplifiers are given in Table II. The keys to efficient operation of Helios are the use of an external electron beam to control the electric discharge for optimum laser excitation and the triple optical path through the laser gas, allowing the Power Amplifier Module (PAM) to serve as both preamplifier and power amplifier.

The next-generation CO_2 laser is Antares, currently under construction at a 40KJ energy level but originally designed to achieve 100KJ in a 1ns pulse. This laser employs an annular geometry, with an electron gun in the middle of the PAM and segmented gain regions in an annulus around the e-guns. In the context of this Conference, the Antares technology is more similar to that of a single-pulse research-oriented machine than to the efficient, repetitive systems required for commercial power production.

A. Future Systems

Several major studies have been conducted on the cost and configuration of future CO_2 systems. One by the Avco-Everett Research Lab[2] forms the basis for this discussion of future systems. This study developed a reference design for a commercial class system and permitted the construction of cost estimates for various technology choices. Note that the quoted costs are intended to be relative and are based on mature-technology "nth copy" rather than "first of a kind" cost estimates.

TABLE II
HELIOS OPERATIONAL PARAMETERS

Gas Mixture	CO_2, N_2, He, 3/1/4/1 ratio, 1800 torr pressure
Discharge	200Kv, 10A/cm^2 3?s duration, controlled by 300Kv, 1A/cm^2 electron beam ionization.
Dimensions	34cm square optical aperture, 2m long

Two factors had a strong influence on the design concept:

> Because repetetive operation requires gas flow and cooling, and because the major efficiency losses in gas flow arise from turning the gas flow, a large wind-tunnel-like design was proposed, Fig. 1.
>
> Because CO_2 is a storage laser, the Power Amplifier energy is not available in a single 1ns pulse; therefore, the 1-ns pulse was propagated four times through the amplifier, with interpass delays of several hundred nanoseconds.

This system concept was sized and costed for various combinations of several other important factors--the repetition rate, the laser gas pressure and the choice of pressure interface window. Predicted costs and efficiencies are presented in Table III.

In the Avco design, typical PAM parameters are:

1MV	discharge voltage
3.3m	long m optical direction
1.6m	wide electric discharge direction
3m	high or. gas flow direction
4?s	electrical pulse length 90.5 atm)

The discharge voltage was chosen as high as practicable under reasonable technology forecasts. The height in the gas flow direction decreased at the higher repetition rates in order to minimize gas flow power consumption. The desired electrical pulse length varied inversely with the laser pressure, due to faster molecular kinetics at higher pressures.

TABLE III
COSTS AND EFFICIENCIES OF 1.2MJ CO_2 LASER FOR VARIOUS REPETITION RATES AND DESIGN CHOICES

Gas Pressure (atm)	Repetition Rate (Hz)	Aerowindows		Salt Windows	
		Cost ($ Million)	Efficiency (%)	Cost ($ Million)	Efficiency (%)
0.5	2	229	6.04	268	8.09
0.5	10	263	7.52	303	8.03
0.5	40	550	8.13	596	8.16
1.0	10	132	7.6	168	8.3
1.0	40	308	8.5	353	8.5

B. Key Technologies

The results in Table III focus attention on the key technology issues for the CO_2 laser.

1. Pulsed Power. It is clear from Table III that higher pressures are advantageous in both cost and efficiency; however, a 1atm pressure required an electrical pulse length of 2μs. These advantages result primarily from the fact that higher-pressure PAMs produce more laser energy per unit volume (pressure) and hence have lower capital costs and less gas flow losses.

There are, however, serious questions on the viability of the shorter electrical pulse technology. 1A pulsed power system based upon thyration switching and pulse transformers is assumed for electrical lengths 7.4μs, and it is predicted that this combination is feasible with long lifetimes based on today's technology. Risetime and peak-current requirements become more stringent for shorter electrical pulses, causing a design shift to pulse-forming network coupled directly to the PAM, with spark-gap or stacked-ignition switching. Because of limited spark-gap life and uncertainties in use and triggering of series-stacked ignitrons, the higher pressure PAM option is viewed as riskier, and the potential payoff of developing long-life high-current components for use at ~2μs pulse lengths is clear from Table III.

2. Pressure-Interface Windows. The cost, efficiency, life and feasibility of pressure-interface windows are important factors. Although Table III indicates a cost advantage to aerodynamic windows and an efficiency advantage to salt windows, there are many issues to be resolved.

Salt (NaCl) windows consume no power, but have cost and size limitations. Their life is uncertain but their advantages strengthen at high pressures, which increase the power consumption of aerodynamic windows. The Avco study assumed state-of-the-art NaCl windows arranged in a mosaic to achieve the desired size, with an energy loading of $1 J/cm^2$, half the design point of present single-pulse systems. The primary issues are the life of salt flats and the ability to maintain spatial coherence of a laser pulse as it propagates through a segmented window.

Aerodynamic windows can be viewed as regions of curved gas flow, in which the centrifugal force of the curved flow can support a pressure difference across the flow. Both supersonic and subsonic "aerowindows" have been built, typically in apertures up to 10cm across. Their prior applications have been in systems in which the total mass flow of gas must be minimized; these windows consume large powers. Estimates based on reoptimizing aerowindows to minimize power consumption give ~15 - 30MW per square meter of aperture per atmosphere of pressure difference. The estimates in Table III use the lower figure. Because of this high power consumption, the Avco design with aerowindows utilizes a single aerowindow of .6m^2 aperture for the entire laser; beams from the various PAMs are sent through at different times and angles to prevent gas breakdown. The critical issues are the scaling of aerowindows by ~ two orders of magnitude in area from present sizes, redesign to minimize power consumption, and the actual laser fluence limit in preventing laser-induced gas breakdown.

Other Issues. Because the Co_2 laser has proceeded through several generations of short-pulse systems, the future technology issues reflect primarily the requirements for reliable, efficient, repetitive operation. The scaling of atmospheric-pressure discharge to square-meter and larger apertures, and the value of an imposed magnetic field, is an important issue. Although micromachined copper-surface mirrors appear to meet the efficiency and lifetime requirements, work is required in the cooling of mirrors under repetitive operation. There is a wide field of exploration required in the design of integrated optical systems, involving automatic alignment and beam-quality-correcting optics. Concepts for control of temperatures and density fluctuations in gases must be engineered to prevent laser beam focusability degradation by random gas fluctuations. Advances are required in the life of electron-beam foil windows, through which the discharge-controlling electron beams pass.

The Future. In the development of ICF, a megajouse-class single-pulse CO_2 laser will be needed if CO_2 remains a viable candidate. It is expected that discharge-scaling and efficient energy extraction studies will influence its design markedly. Some of the technology requirements are being addressed for other applications, but a comprehensive program to develop the CO_2 laser's potential as an ICF driver will lickely await a national commitment to a repetitively operated facility, e.g., an Engineering Test Facility.

III. THE KRYPTON FLUORIDE LASER

In the presence of an energetic electron beam, krypton and fluorine can form a bound, excited molecule:

$e + Kr \rightarrow Kr^+ + 2e$
$e + F_2 \rightarrow F^- + F$
$Kr^+ + F^- \rightarrow KrF^*$

The excited KrF molecule has a high probability of dissociating by emission of one photon, so this process populates the upper laser level and atomic repulsion destroys the lower laser level, thus allowing optical gain.[3] The KrF laser operates at 0.249μm, considered by many to be an ideal wavelength to drive ICF pellets.

Unlike CO_2, the KrF laser is not a storage laser; the spontaneous lifetime of KrF* is 3ns, and this fact has a substantial impact on design concepts for KrF. The theoretical efficiency limit is 24Δ, with 2Δ demonstrated and 8 - 10Δ projected. Typical operating parameters are given in Table IV.

Because the KrF* molecule lives only 3ns, there must always be a saturating laser field present or energy and efficiency will be lost. There is therefore a fundamental requirement that some pulse compression scheme be employed to convert the 300ns system operation into ~10ns pulses. One method is optical angular multiplexing,[4] by which a sequence of 30 pulses, each 10ns long, saturates the amplifier in turn; because the pulses pass through the amplifier at differeng angles, they will separate physically and can then be delayed to arrive simultaneously on a pellet.

A second compression scheme, which can be used in conjunction with the first, is Raman pulse compression.[5] This is a nonlinear process which occurs in a high-pressure methane cell. A high-power KrF laser pulse (λ = 0.249μm) and a shorter, lower-power "stokes" pulse (λ = 0.268μm) travel against each other in the methane cell. Through the nonlinear Raman interaction, the shorter Stokes pulse depletes the energy in the laser pulse as they travel past each other, thereby in effect compressing the laser pulse.

TABLE IV
TYPICAL KrF LASER OPERATING PARAMETERS

Gas Mixture	$Ar/Kr/F2$ 700/100/10 torr
Electron-Beam Excited voltage > 200kV current 30A/cm^2 pulse length 300ns	
Peak Power Output	10 - 100 MW/cm^2

There is a tradeoff between compression ratio and conversion efficiency which is, e.g., 12 x compression at 50Δ or 8 x at 70Δ. An advantage of Raman pulse compression is its tolerance for low-optical-quality laser pulses, thus removing some burden from the optics which precede it.

Yet another approach is to use one of these schemes with a much shorter (e.g., 50ns, 2500 torr pressure) excitation, but several performance parameters remain to be proven.

The most advanced short-pulse KrF laser is RAPIER at Livermore.[6] Its present and planned operating parameters are given in Table V. At present, the KrF development work is decoupled from the ICF pellet physics work, because the latter can proceed with frequency-tripled or-quadrupled light from Nd-glass lasers.

A. Future Systems.

Several recent studies have addressed megajoule-class KrF laser design concepts. These studies have included pure angular multiplex and hybrid multiplex/Raman compression systems.[7,8]

The study which addressed near-commercial-class requirements was conducted by Livermore, Bechtel, PI and Hughes Aircraft. Aimed at an Engineering Test Facility design, this study developed a concept to produce 1.5MJ, deliverable in 20ns, operating at 2Hz with an estimated efficiency of 3Δ and life of 10^7 pulses. The design calls for 14 PAMs, with characteristics given in Table VI. A single methane cell 15m long with an optical aperture of 3.3 x 11.6m provides a 5x pulse compression at 80Δ efficiency for all the laser pulses. A pulse-forming line provides the electrical excitation and each PAM has a laser gas flow loop. The optical windows are Suprasil, 10cm thick, with four 1m x 1m windows in a square array on each end of each PAM. System mirrors are dielectric-coated aluminum.

TABLE V
RAPIER PARAMETERS

Front End Output	1J in 30ns
A Amplifier	
volume	5 liters
excitation	two opposing electron-beam guns, each 300kV, 100A/cm^2
output	15J in 20ns 3-pulse multiplex
B Amplifier (planned)	
output goal	200J in 50ns; 100J in Stokes pulse

TABLE VI
KrF PAM PARAMETERS

Dimensions	3m long 2m x 2m aperture
Excitation	
electron beam	1.3MV 25 A/cm^2 400ns duration
optical	Four 100ns pulses amplified
Energy Output	160KJ

B. Key Issues.

Because present-generation KrF KF systems produce only ~10J, there are both fundamental and technological issues in scaling them to the megajoule level.

1. Optics. Laser damage to optical elements is an important issue. Because of the short wavelength, multilayer dielectric coatings are required to achieve high-reflectivity mirrors and highly transmissive windows. The highest single-pulse damage thresholds, for 22ns pulses, are 3.6J/cm^2 for reflectors and 10.8J/cm^2 for windows.[9] The damage mechanism is electric-field dependent. Window size limits of 0.5 to 1m-diameter are projected, and the application of uniform dielectric coatings over such areas is an issue. The effect of fluorine on the optical elements must be considered.

2. Discharge Scalability. The short lifetime of KrF* produces significant amounts of amplified spontaneous emission (ASE), comparable in power to the laser pulse output. Control of ASE and parasite oscillations is necessary to maintain system efficiency and to prevent prepulse energy from destroying the pellet. Magnetic fields will be needed to control pinching of the electron-beam excitation. Survival of the electron gun and foil window are a greater issue here than with CO_2 because the electron gun provides the entire excitation. Greater understanding of the fundamental KrF kinetics will be required to permit optimization and prediction of PAM performance in larger sizes.

3. Pulsed Power. This system uses a Marx-generator source, which charges an intermediate-storage (~2μs) water-insulated line, which in turn drives a fast pulse-forming line. Gas switches are assumed, but such high-power switches are only in development for single-shot operation only. The short excitation pulses require low-jitter switches for correct timing.

New developments in electron-beam cathodes (Maxwell's carbon-felt cathode, S^3's spark cathode), but long-lived electron-beam foils will require development.

4. Other Issues. At the potential risk of greater complexity, 50-fold optically multiplexed PAMs may be considered, to avoid the need for Raman compression. Scaling and improvement of Raman compressor performance will require the suppression of other nonlinear processes, e.g., the power loss to the second-Stokes frequency. Especially in highly-multiplexed KrF systems, there is a potential for optical "crosstalk" between angularly adjacent beams, which could generate unwanted prepulse or parasitic energy. Any decrease in the required laser pulse length would require greater pulse compressions, hence a more complex optical system.

IV. OTHER LASER CANDIDATES

The Xe Cl excimer laser is very similar to the KrF laser, with two important exceptions: its wavelength is 308 μm and its demonstrated intrinsic efficiency is only 5%. The wavelength may be an important advantage because of an empirical λ^4 variation of laser damage thresholds on optical materials in this wavelength region. There is a possibility that a thorough investigation of its kinetics will indicate improvements in efficiency, but Xe Cl is clearly receiving less attention than KrF.

The free-electron laser[10] operates by passing a stream of bunched electrons through a region of spatially-varying static magnetic field (a "wiggler"). By controlling the electron energy, optical gain can be created at any wavelength. Although only ~10% of the electron energy can be converted to laser energy, recovery of the unused laser energy might increase total system efficiency to ~25%. Two applications of free-electron lasers to ICF have been discussed. In one, ms-length laser pulses would be generated and optically pump another laser medium, from which shorter pulses would be extracted to drive the pellets. The other would use a pulsed accelerator, e.g., a Betatron or induction linac, to provide a 600ns long electron beam. This beam would be split into sixty 10-ns pulses, each of which would pass through its own wiggler aimed directly at the pellet. The economics and technical feasibility of these possibilities remain uncertain.

V. CONCLUSION

Uncertainties in both laser-pellet interaction physics and ultimte laser technology and performance will prevent a near-term choice of the best laser driver candidate for ICF. At the same time, significant light-ion-driven experiments are planned and the heavy-ion-driver program will require pellet physics tests. Thus, although the greatest uncertainties in ICF are in the pellet physics area, we cannot assume that the "right" driver will exist without continuing the investigation of the major driver candidates.

REFERENCES

1. E. E. Stark, Jr., "Lasers and Power Systems for Inertial Confinement Fusion Reactors," ANS Third Topical Meeting on the Technology of Controlled Fusion, May 9-11, 1978, Santa Fe, NM.

2. H. W. Friedman, "Fusion Driver Study--Final Technical Report," April, 1980, Performed under contract DOE/DP/40006 by the Avco Everett Research Laboratory for the U.S. DOE.

3. J. J. Ewing, C. 1A. Brau, Applied Physics Letters 27, 350, 1975.

4. J. J. Ewing, R. A. Haas, J. C. Swingle, E. V. George, W. 1F. Krupke, "Optical Pulse Compressor Systems for KrF," IEEE JQE, QE-15, 368, 1979.

5. J. Murray, J. Goldhar, D. Eimerl, A. Szoke, "Raman Pulse Compression of Excimer Lasers For Application to Laser Fusion," IEEE JQE, QE 15, 342, 1979.

6. J. J. Ewing, "RAPIER: An Optical Pulse Compressor," LLL Energy and Technology Review, p. 16, June, 1979.

7. R. A. Haas, L. G. Seppala, L. D. Pleasance, E. V. George, W. 1F. Krupke, "KrF Fusion Laser System Design. 1: General Performance Characteristics of Stackes/Raman Compressor Laser Systems," Paper TUF11, Topical Meeting on Inertial Confinement Fusion, San Diego, February 26-28, 1980.

8. J. A. Caird, W. O. Allen, H. G. Hipkin, M. R. Flannery, G. M. Perron, S. N. Suchard, D. E. Vandenburg, J. Benford, Y. G. Chen, D. Dummings, D. Dakin, P. Spence, "KrF Fusion Laser System Design. 2: Engineering and Economic Analysis," Paper TUF12, Topical Meeting on Inertial Confinement Fusion, San Diego, February 26-28, 1980.

9. D. H. Gill, B. E. Newman, "Damage Resistance of UV Coatings," Laser Focus, September, 1979, p. 76.

10. "Workshop on Free-Electron Generators of Coherent Radiation," Telluride, Colorado, August 13-17, 1979.

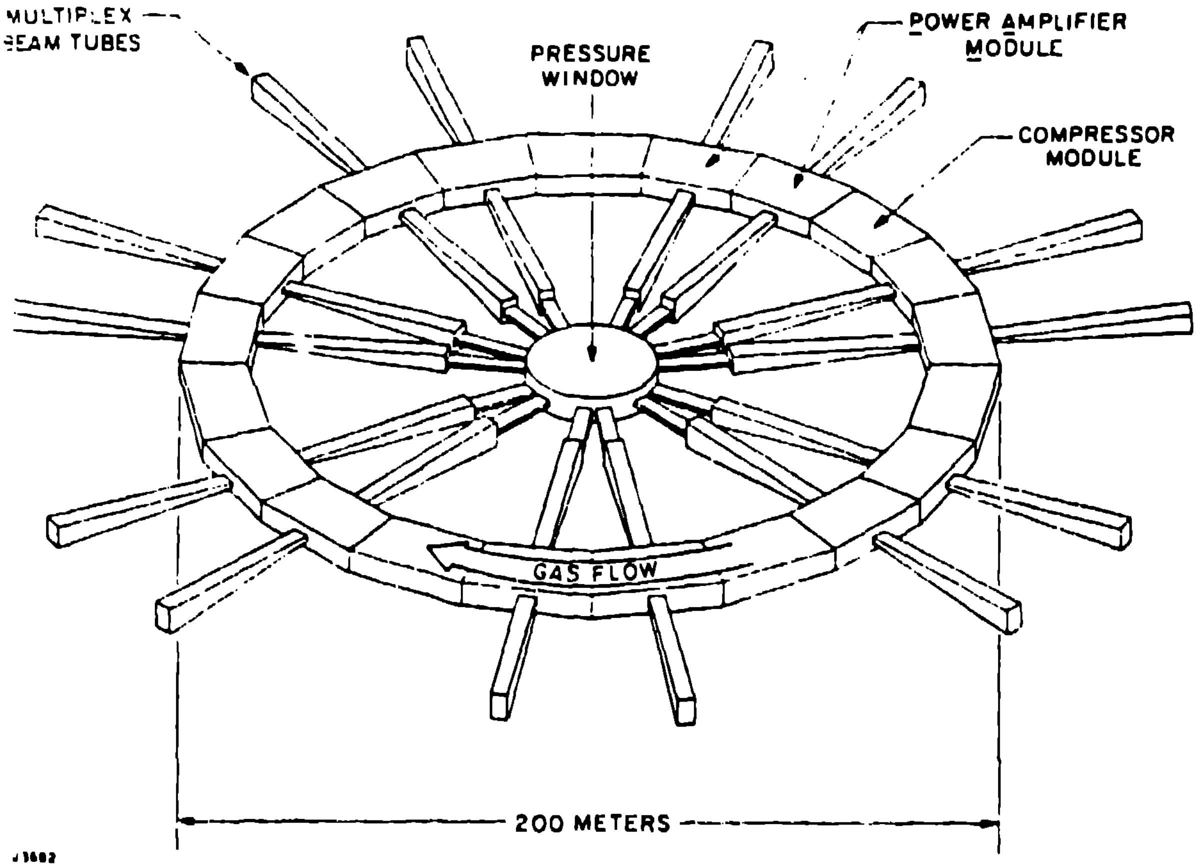

Figure 3 Overall Layout for 1 MJ Fusion Driver System