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DEVELOPMENT OF KrF LASERS FOR FUSION

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ABSTRACT

Short-pulse, high-intensity excimer lasers are being developed for a variety of atomic physics and inertial confinement fusion applications. In this paper, we will discuss the status of KrF laser technology and its application to ICF. Current progress worldwide will be described with emphasis on the Los Alamos program.

Introduction

The Los Alamos National Laboratory has been actively engaged in the development of high-power gas lasers for inertial confinement fusion applications for twenty years beginning with the highly efficient long wavelength CO_2 laser. Based on results from the target experimental programs in the early 1980s, a national shift in the required laser wavelength occurred, and the Los Alamos ir laser program was terminated in favor of the short wavelength KrF gas laser.

The KrF laser is relatively new to the ICF community; it was demonstrated in 1975 (Brau and Ewing 1975), followed immediately by other confirmations of spectroscopy and lasing (Brau 1975; Ewing and Brau 1975; Ault et al. 1975; Mangano and Jacob 1975; Searles and Hart 1975; and Tisone et al. 1975). The development of high peak power KrF laser technology for Inertial Confinement Fusion (ICF) applications is actively in progress throughout the world with major facilities underway in Japan, Canada, England, the USSR, and the US. Because of the newness of the technology, most of these efforts are a strong mixture of facility engineering, advanced technology research and development, and advanced conceptual design studies. The Los Alamos National Laboratory KrF laser development program is probably the largest effort in the world. It addresses both near-term integrated laser demonstrations and longer-term advanced design concepts and technology advancements required for larger fusion laser systems. We will review the basic features of the KrF lasers, describe the status of the worldwide KrF technology program, provide an overview of the Los Alamos laser development program, describe current progress on the near-term technical activities, and discuss the future directions of the Los Alamos KrF laser development program.

Basic Features of the KrF Laser

KrF lasers operate by electrically pumping high-pressure gas mixtures of krypton (Kr), fluorine (F_2), and a ballast gas such as argon (Ar) with self-sustained electrical discharges or with high-energy electron-beams. The electrical excitation initiates a complex chain of reactions that results in the production of the krypton fluoride (KrF*) molecule and various absorbers. The KrF* molecule can then lase to the unbound lower level, emitting a photon at 248 nm. The upper state lifetime is very fast in the excited KrF molecule, and storage times are limited to approximately 5 ns by quenching and spontaneous emission. KrF is the second most efficient member of a class of excimer lasers that also include the well-studied XeCl (lasing at 308 nm), XeF (lasing at 351 nm), and ArF (lasing at 193 nm), which is the most efficient.

A unique combination of features appears to make the KrF laser well suited as a driver for inertial confinement fusion drivers. These features are summarized below.

- The laser directly operates at 248 nm, optimizing the ICF target efficiency without added wavelength conversion complexity.
- Unlike other ICF lasers, the KrF laser is basically not a storage laser; it prefers to operate in the continuous energy extraction mod Because of this feature, loaded KrF amplifiers tend to be very linear with little temporal pulse shape distortion. This allows for very robust pulse-shaping capability that may prove absolutely essential for efficient target performance.
- Electron-beam pumped KrF lasers are scalable to large energies in a single module. This feature has been clearly demonstrated by amplifier architectures now under development. The Aurora large aperture module has already demonstrated 10 kJ extracted from a 2000 l volume, and advanced Los Alamos designs will explore amplifiers in the 50-kJ to 250-kJ region.
- The laser operates with a broad lasing bandwidth in excess of 200 cm^{-1} that allows the use of spatial and temporal smoothing techniques for both direct and indirect target drive applications.
- Although all of the current ICF related KrF laser technology development programs are emphasizing single-shot facilities, the basic design features of the KrF gas laser will permit extensions to repetitively pulsed devices in the future, if commercial energy applications are pursued.
- The laser medium is a non-damaging gas, eliminating the need for extensive protection systems to insure the survivability of the laser medium. This feature also allows KrF to readily adapt to multiple-pulse operation for commercial applications.

Worldwide Progress

Since their invention in 1975 by Brau and Ewing, excimer lasers have been the subject of steady and increasing interest. Major progress has been made in the commercial development of high average power devices, with 1-kW devices being actively developed on several continents through individual companies or industrial consortia. More recent interest has centered on the development of high peak power devices as potential replacements for harmonically converted glass lasers in inertial confinement fusion and extremely high intensity atomic physics applications. Active research and technology programs are in progress in the United States and competitive programs are being pursued in Japan, Canada, Germany, the United Kingdom, and the Soviet Union. These programs have led to a series of first-generation, integrated laser-target systems that are in design, construction, or testing. Table 1 shows a current compilation of these laser systems. The Lawrence Livermore National Laboratory (LLNL) RAPIER system was operated briefly in the early 1980s and then decommissioned. The SPRITE laser, built at the Rutherford-Appelton Laboratories in the United Kingdom, was the first truly high-power KrF facility in operation. The UK government is considering an upgrade of this facility to the 3-kJ level and designs are currently in progress for a 100-kJ Euro-laser option based on KrF. The Naval Research Laboratory (NRL) is the other Department of Energy (DOE) US participant in the KrF laser development program. NRL has started construction of the NIKE laser that will produce 2 to 4 kJ. The University of Alberta at Edmonton is proposing to build a 1-kJ facility, utilizing some of the components from the LLNL RAPIER laser that have been provided by the DOE through a joint US/Canada protocol. Several Japanese universities are actively involved in the pursuit of KrF lasers; the major operating facility in operation is the ASHURA laser at the Electro-Technical Laboratory of the University of Tokyo. In addition, the Kurchatov Institute of the USSR is constructing a kJ-class KrF facility in collaboration with Evremov Electro-Technical Institute and is pursuing conceptual designs for a 10-kJ class device. All of these facilities are based on electron-beam pumped KrF laser technology; they employ several different optical architectures and different design philosophies. This broad array of activities will continue to enrich the technology available to KrF lasers and to improve the performance and reduce the cost of many system components.

TABLE 1. KrF Laser Technology Is Being Pursued Internationally for ICF Applications

Laser System	Status	Energy	Power
Rapier (LLNL)	1982	800J	1×10^{10}W
SPRITE (Rutherford)	1983	200J	3×10^{9}W
Euro-Laser (Rutherford)	~1996	100kJ	variable
AURORA	1985	10kJ	2×10^{10}W
(Los Alamos)	1988	1kJ	2×10^{11}W
	1989	4kJ	10^{12}W
Nike	1989	10J	------
(NRL)	~1993	2kJ	------
Rapier B	1988	100J	-------
(U of Alberta)	(proposed)	1kJ	-------
Ashura (Electro-Technical	1988	500J	5×10^{9}W
Lab, Japan)	(future)	1kJ	2×10^{11}W

Overview of KrF Laser Development Program

In the preceding we have discussed both the potential advantages of KrF lasers and the international effort now underway in KrF laser technology. The potential advantages of the laser are well recognized, but they must be demonstrated at current scale size in integrated laser-target systems. More importantly, these advantages must be shown to scale economically to the 100-kJ to 10-MJ sizes required for future progress in the ICF program. The Los Alamos laser development program is composed of three major elements that are intended both to aggressively address near-term feasibility of the KrF laser concept and to show the way to the cost and performance improvements required for future laser facilities.

- The Aurora Laser Facility is a 1-TW KrF laser designed as an integrated performance demonstration of a target-qualified excimer laser system.
- An advanced design effort evaluates the concepts that offer the improved performance and lower cost that will be essential for the construction of future lasers in the 0.1- to 10-MJ class.
- A laser technology program addresses both performance and cost issues that will be important in advanced laser system designs.

Each of these programs is briefly described below.

Aurora

The near-term goal for Los Alamos is the successful integration and operation of the of the Aurora Laser Facility at the multi-kilojoule level with powers approaching 1 TW. Aurora is a short-pulse, high-power, krypton-fluoride laser system. It serves as an end-to-end technology demonstration prototype for large-scale excimer laser systems of interest to short wavelength ICF investigations. The system employs optical angular multiplexing and serial amplification by electron-beam driven KrF laser amplifiers to deliver multi-kilojoule laser pulses of 248 nm and 5-ns duration to ICF relevant targets. The design goal for the complete system is 5 kJ in 48 laser beams. Figure 1 shows a conceptual schematic diagram of an angularly multiplexed laser system showing a single front end pulse being split into three replicas, delayed, angularly encoded and then feed to a power amplifier for efficient, quasi-cw energy extraction. Figure 2 shows the floor plan of the Aurora Facility with the laser bay to the right, target chamber to the left and the optical beam transport system in the long tunnel connecting the two subsystems.

Substantial progress has been made on the facility in the last several years including the following highlights:

- Demonstration of 96-beam multiplexing and amplified energy extraction, as evidenced by the integrated operation of the front end, the multiplexer (12-fold and 8-fold encoders), the optical relay train, and three electron-beam driven amplifiers;
- Assembly and installation of the demultiplexer optical hardware, which consists of over 300 optical components ranging in size from several centimeters square to over a meter square;
- Completion of pulsed-power and electron-beam pumping upgrades on the LAM (Large Aperture Module), PA (Pre-Amplifier), and Small Aperture Module (SAM). The SAM shows a 40% increase in deposited electron beam energy, and the PA deposited energy has been increased by a factor of two; and
- Integration of the entire laser system; the extraction of 4 kJ from the laser in 96 beams; and the delivery of 1.3-kJ to the target chamber in 36 beams with intensities in excess of 100 TW/cm^2 in pulse durations adjustable between 3 and 7 ns.

Advanced Laser System Design

In the longer term, the national ICF program will continue to plan for the construction and operation of the next generation driver for ICF physics experiments. To determine the applicability of KrF laser technology to future generations of fusion drivers, Los Alamos has begun a design effort to explore systems in the 100kJ to 10MJ range. This Advanced KrF Laser Design effort provides information to the KrF program on the design and cost of future KrF laser-fusion systems and provides directions and goals to the KrF technology development effort. Because no current ICF driver has demonstrated both the required cost and the performance scaling, and because uncertainties exist in laser-matter interactions and target physics, Los Alamos is currently pursuing a range of advanced KrF laser design activities: work is currently in progress to scope a 10-MJ Laboratory Microfusion Facility (LMF), a 750-kJ LMF Prototype Beam Line, a 250-kJ Amplifier Module (AM), and a 100-kJ Laser Target Test Facility.

The purpose of the Department of Energy sponsored scoping study for a Laboratory Microfusion Facility is to examine a facility with a capability of producing a target yield of 1000 MJ in a single-pulse mode. An example of a KrF design for an LMF beam line that requires only minor extrapolations in pulsed-power technology is shown in Fig. 3. This system uses angularly multiplexed amplifier modules 1.3 x 3.9 x 3.8 m^3, each of which produces 250 J of 248-nm radiation. These units are then arranged in a tri-fold cluster, to form an LMF beam line that produces 750 kJ. These beam lines can then be arranged to produce the total required energy ranging from 750 kJ to 10 MJ.

KrF Technology

The current costs of all laser drivers are unacceptable for an LMF scale system. To reduce these costs to an acceptable level, advanced technology programs are being designed to address the major cost drivers identified by the LMF studies. Optics and pulse power account for 60% of the total cost for the Aurora design; this produces an unacceptably high laser system cost when scaled to larger facilities. Advanced design concepts have identified technology areas that can be improved to reduce the overall system costs. The optics and pulse power costs have been reduced to 19% of the total system cost, and the total subsystem cost is reduced by a factor of 5. The KrF laser technology development program addresses performance improvements and cost reductions for the LMF designs in the areas of optics, pulse power, and laser performance, as well as those technical issues effecting system reliability and modeling accuracy. These improvements include increases in the optical damage fluences for uv radiation from the current value of 12 J/cm^2 to 20 J/cm^2 (20-ns pulses @ 248 nm); increases in power amplifier size from the current 10-kJ modules used in Aurora to units in the 50- to 250-kJ class; and electron beam pumping densities in the 125 to 175 J/l range with intrinsic efficiencies in excess of 10%. These technology and cost reduction programs will utilize a mixture of industrial, university, and government laboratory involvement and could lead to the required subscale technology demonstrations in the next three- to five-year period.

Conclusion

High-energy, high-peak power KrF lasers represent a promising new technology for inertial confinement fusion applications. To evaluate this technology, Los Alamos is conducting a series of integrated system demonstrations with the Aurora Laser Fusion facility. Future ICF applications of the KrF laser are being evaluated by a coordinated program of advanced designs and technology development. If these evaluations are successful, KrF lasers will provide the national ICF program with an attractive future driver candidate for the Laboratory Microfusion Facility in the late 1990s.

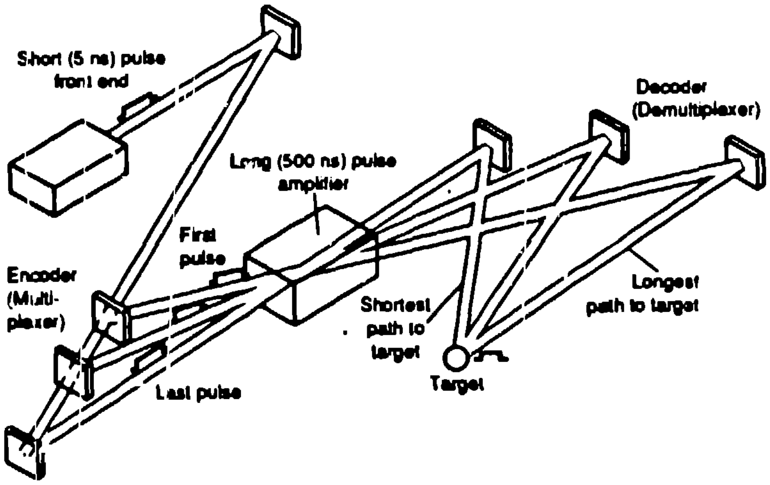

Fig. 1. Angular optical multiplexing allows for efficient energy extraction of long pulse amplifiers. A single 5-ns pulse is split and delayed and feed through the 500-ns amplifier. After amplification the angle encoded time channels are recombined in synchronism at the target. In the schematic shown, this technique allows a power multiplication of x 100 when 100 optical channels are used.

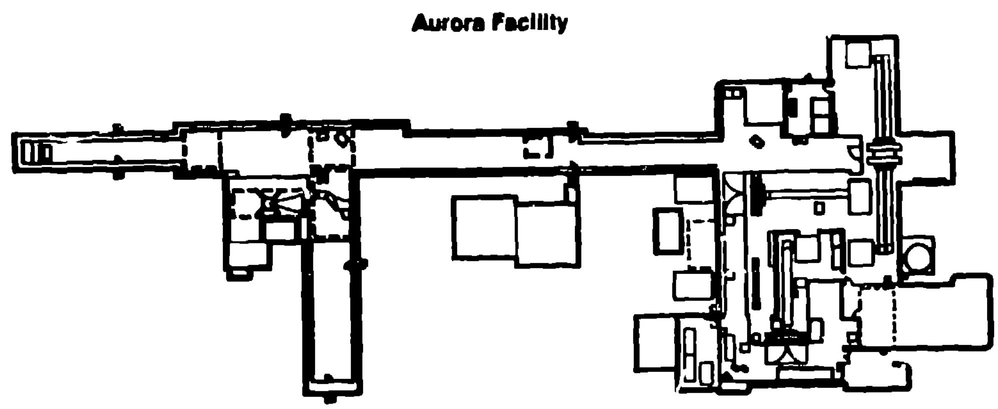

Fig. 2. Schematic of the three major Aurora subsystems: target chamber, beam transport and decoder, and power amplifiers and front end (left to right).

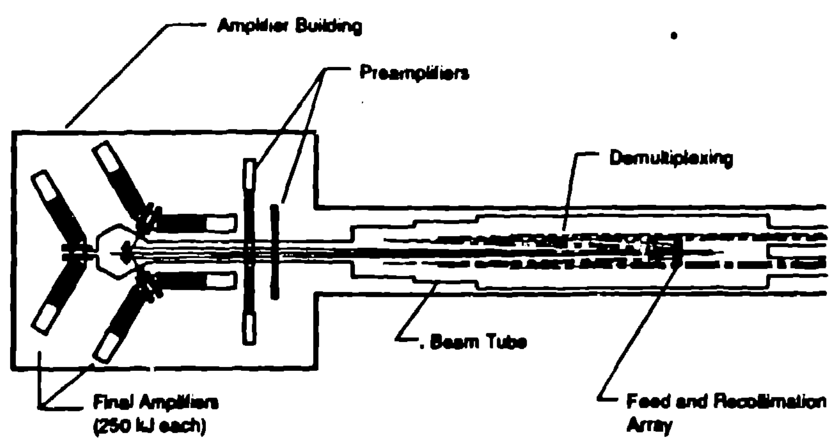

Fig. 3. LMF beam line showing a tri-fold array of 250-kJ modules.

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