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Excimer Laser Development for Fusion

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ABSTRACT

The future utility of inertial confinement fusion requires a new driver. Successful experiments coupling laser energy to targets, and our understanding of fuel capsule behavior strongly suggest that a Laboratory thermonuclear source is attainable and power production may be considered if a suitable driver with high efficiency, high repetition rate, and most importantly, low capital cost, can be identified. No adequate driver exists today; however, the krypton fluoride laser holds great promise. By the end of this decade, driver development can be brought to the point that a technically justifiable choice can be made for the future direction of ICF.

The understanding we have gained through research on inertial confinement fusion (ICF) has led us to a rather well substantiated and stringent set of requirements. We now know, for example, that for ICF to represent a potential future large-scale energy source, we need: 1) a driver with a wall-plug efficiency (drive energy out compared to electrical energy input) of at least 7% at a repetition rate greater than 5 Hz, 2) a target gain such that the product of target gain and driver efficiency exceeds 5, and 3) a strong technical justification for eventual low capital cost. In fact these requirements depend on what other alternative power sources are available in the next century, but generally they represent a set of minimum criteria which must be met if ICF is to be an economically competitive source of energy.

Although we have made great progress in our understanding of driver-target coupling and in the design of fusion capsules, we today have no driver capable of testing our high-gain designs, and certainly no proven driver which could be scaled to use in power production. One of the most promising drivers to be considered, the CO₂ laser, was indeed efficient, scalable, and capable of high repetition rate operation. However, detailed examination of the physics involved when high intensity long wavelength laser light irradiates target materials has shown that significantly shorter wavelengths than that obtainable from CO₂ lasers will be necessary as well. In fact, our data and calculations have shown that, to optimize the laser-target interaction process we would prefer to have a wavelength in the region of 200 nm.

Ion drivers have been considered for some time, and such drivers have the immediate advantage of high efficiency. Light ion drivers offer low capital cost but have not been able to demonstrate either high power density, high

repetition rate, adequate temporal history of the pulse, or sufficient stand-off distance between target and driver. Work continues at several laboratories to address and solve these problems, but we cannot be guaranteed of successful solutions today. Heavy ion drivers offer the potential of high efficiency and high repetition rate but at considerably higher cost than light ion drivers and the issues of obtaining adequate stand-off (beam propagation) and pulse shaping are still major questions.

Lasers, with their coherent output are focusable to high power densities and provide the necessary target stand-off; but to find a single laser which satisfies all necessary ICF criteria at once is not a simple exercise. After an exhaustive examination of possible laser candidates we have come to the conclusion that the krypton fluoride (KrF) excimer laser holds great promise as a future ICF driver.

The KrF laser can be constructed with a high efficiency, exceeding 8%, and a high pulse repetition rate, since the lasing medium is a gas. Its output at 248 nm is near optimum for coupling to ICF targets, without any added complications of wavelength shifting. A detailed examination of the costs for a large KrF laser suggest that a total system cost of less than \$90/J should be possible for a laser which produces 10 MJ output, in a short, temporally shaped pulse. Achieving such a low cost will require development of manufacturing capabilities to incorporate known techniques for the production of large optical components.

There are, of course, technical issues associated with the KrF laser which must be addressed before a definite statement can be made as to their future use in ICF. Moderately large KrF lasers have been constructed, but issues of scaling to very large size while maintaining (and improving, somewhat) overall efficiency have yet to be addressed experimentally. Since

the excimer is not a storage laser, some technique must be used to obtain the short pulses, with the required temporal dependence necessary for fusion. This must be done without sacrificing either efficiency or cost. There are two approaches which have been identified to accomplish the necessary pulse shortening--optical angular multiplexing or Raman, nonlinear compression. Since we expect a significant loss in efficiency with a nonlinear optical scheme, we have chosen optical multiplexing as the most likely technique to meet the ICF requirements.

Using optical multiplexing provides a large number of individual beamlets which can be added together at the target with suitable individual delays to obtain a required temporal pulse shape. In fact, our calculations tell us that with only twenty-two beamlets passing sequentially through a high-efficiency amplifier we can reconstruct a temporal shape required for one of the most demanding high-gain target designs. The individual beamlets are not all of the same time duration but the production of such segments is a relatively simple exercise in the front end of the laser system.

The optical complexity introduced by multiplexing is another issue to be addressed because of the apparent large number of control points involved. Optical multiplexing is an issue which would probably be faced with any large laser system since it would be required to obtain adequate efficiency by multipassing amplifiers. With the KrF laser, we are addressing this question from the start. The optical design we have developed requires that only four mirrors be controlled for each beamlet throughout the system, a number comparable to many other multibeam laser systems. In a recent test we have demonstrated the simultaneous alignment of 96 beams to 5 μ rad precision in a total of eight minutes. Individual mirror motions were controlled by a small computer which also performed the

image analysis, making use of statistical techniques employing inherent noise. This alignment scheme is being incorporated into an end-to-end laser system which will demonstrate operation of a complete KrF laser architecture and its utility for ICF target experiments.

Efficiencies of four to seven percent have been demonstrated. We believe, for single pulse operation, this efficiency can be increased to greater than ten percent principally by advances to be made in the deposition of electrical energy into the laser gas and increases in the intrinsic efficiency. Since the KrF laser is pumped by electron beam deposition into the krypton fluoride gas mixture, significant efficiency improvements can be made if care is taken to make use of all electrons emitted from the cathode. Segmented cathodes, expanding flow (B field embedded) diodes, and properly chosen electron beam window support geometries can improve electrical energy deposition by approximately 25%. Using krypton-rich gas mixtures will improve the intrinsic laser efficiency from 11% to 16%.

Another important issue, as we mentioned, is cost. KrF amplifiers, and, as we have demonstrated, control systems are relatively inexpensive. However, a major cost is that for optics, in particular the ultraviolet optics required to operate at 248 nm wavelengths. The manufacture of optics for a very large laser system would, of course, require increased manufacturing capability. In collaboration with industrial optics manufacturers we have determined that large optics (two meter diameter) could be manufactured for less than $\$20/\text{cm}^2$ using conventional technologies. If new (but demonstrated) techniques were employed for substrate production, coating and polishing, this cost could be brought down to less than $\$10/\text{cm}^2$. Incorporating these costs into a conceptual design for a 10 MJ output KrF

laser system leads us to a total optics cost which is just 24% of the total system cost. This system assumes operation at a fluence of 3 J/cm^2 at the most stressing point.

In a program we have carried out for the past three years to identify damage mechanisms in ultraviolet optics and use that information to attempt to improve optical coatings, we have been able to increase damage thresholds to acceptable levels. Both high reflectance and anti-reflectance coatings, either fluorine compatible (for use in amplifiers) or not have been studied. Anti-reflectance coatings for use in nonfluorine environments can now be made with damage thresholds of approximately 12 J/cm^2 while such coatings for use with fluorine show thresholds for damage at about 2.5 J/cm^2 . High reflectance coatings are achievable with 4 J/cm^2 (fluorine compatible) and 7 J/cm^2 (no fluorine) damage thresholds. Utilizing these coatings in the manufacture of large optics would satisfy the requirements for a large KrF fusion laser.

At Los Alamos we are constructing a complete system, named Aurora, which will demonstrate end-to-end operation of a multiplexed KrF laser. This laser will produce in excess of 5 kJ in a short (5 ns) pulse which can be used to irradiate ICF targets. Completion of this system is scheduled for 1987. The final amplifier, named LAM, has been built and operated. This amplifier has a 1m x 1m output aperture and has produced approximately 13 kJ of laser light in a pulse length slightly less than half a microsecond. In this experiment the LAM, which was not designed to demonstrate high efficiency, nevertheless achieved an intrinsic efficiency in excess of 6% and an overall efficiency of greater than 2%. In separate,

smaller experiments, using higher krypton concentrations, intrinsic efficiencies exceeding 13% have been achieved. Aurora will be an integrated test bed for examining: front ends, angular optical multiplexing, beam control, amplifier staging, nonlinear optics and target physics.

An eventual fusion laser capable of driving targets to high gain will require significantly larger amplifier modules than the LAM. At Los Alamos we are progressing toward a large amplifier scaling experiment to address large volume scaling issues including: high intrinsic efficiency in a large volume, minimum magnetic guide field requirements, e-beam diode segmentation (expanding flow), large cathode performance, maintenance and reliability, and advanced mirror and window technology. We expect to have completed this experiment by 1989. That is also the appropriate time scale to have addressed the issues for light ion and other laser drivers as well.

At that time it will be possible to examine all ICF driver technologies to determine if we can indeed look to ICF for a Laboratory thermonuclear source and an eventual source of power.