Krypton Fluoride Laser Development-the Path to an IRE

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I. INTRODUCTION

We have proposed a program to develop a KrF laser system for Inertial Fusion Energy. **Although we discuss only the KrF laser program in this section, it is part of a larger, broad based integrated program that looks at all the issues for Laser Fusion Energy, including the driver, target gain, chamber, target fabrication, target injection, and ultimately, the cost of energy.**

Direct drive with a Krypton-Fluoride (KrF) laser is a promising approach for Fusion Energy: Direct drive target designs under development at NRL show potential for the required high gain [1]; the Nike laser at NRL has demonstrated that a multi-kilojoule, e-beam pumped, KrF laser can be built and that it can produce the very spatially uniform illumination needed for a high gain target [2]; and The Sombrero Power Plant study showed a KrF based system could lead to an economically attractive power plant [3]. These encouraging developments have led us to formulate a plan that leads to an Integrated Research Experiment (IRE).

We envision the IRE to be a system that integrates and addresses the key enabling technologies for a KrF laser fusion power plant. The IRE will consist of a laser beam line, steering mirrors, a target injector, and a chamber. The entire system will run at 5 Hz. **Simply put, the IRE will be an integrated repetitive demonstration that a power plant sized laser can be steered to illuminate a target injected into a reactor chamber environment, and it can do so with the uniformity and precision required for inertial fusion energy.** The “power plant sized” laser will provide the energy, pulse shape control, wall plug efficiency, and target illumination uniformity required for a single beam line of laser fusion power plant. The energy of the beam line will likely be in the range of 50 to 150 kJ, and a fusion power plant will require 20 to 50 identical beam lines. The chamber will have the same type of environment (e.g. gas needed for x-ray shielding, grazing incidence final optics, etc) as envisioned for a power plant. The laser energy and average power on target would be sufficient that this facility could be used for other purposes, such as to examine chamber clearing issues and investigate the response of candidate wall materials to x-ray pulses.

We have formulated a two phase plan to develop the KrF laser. Phase I concentrates on science and technology. It emphasizes those areas that need the most development, such as laser efficiency and durability, and the associated research areas such as materials, solid state electronics, optics, and thin film coatings. Phase II is to build the IRE. Whether we proceed to Phase II will depend on the success of Phase I. As Phase I requires relatively modest resources ($15M/yr for four years), this approach enables us to assess the viability of a KrF laser with only a modest investment.

II. PHASE I: TECHNOLOGY DEVELOPMENT

Phase I has five tasks that are to be carried out in parallel.

A. The Electra Laser

Electra will be a 700 J, 30 cm aperture, 5 Hz rep-rate facility that will be used to develop the technologies that can meet the fusion energy requirements for rep-rate, efficiency, durability, and cost. Electra will be 1-2% of the energy of a power plant size laser beam line, but it will be large enough to develop the required technologies. The main amplifier will be pumped with two 30 cm x 100 cm electron beams, each with V = 500 kV, I = 110 kA, and τ = 100-300 nsec. Electra will use the same type of architecture that would be used in a power plant laser, e.g. double pass laser amplification with double-sided electron beam pumping of the laser gas. This is the same arrangement now being used in the Nike 60 cm amplifier. The main laser components that need to be developed are: a durable, efficient, and cost effective pulsed power system; a durable electron beam emitter; a long life, transparent pressure foil structure to isolate the laser cell from the electron beam diode (the “hibachi”); a recirculator to cool and quiet the laser gas between shots; and long life optical windows. Components that can meet these requirements have been identified [4]. Many have already been developed separately, but not necessarily in a parameter range suitable for fusion energy [4]. Our plan is to develop these components specifically for fusion in a single integrated laser facility. Electra will be built by integrating each component as it is developed.

We will build two complete pulsed power systems for Electra. The first will be based on existing technology and will be finished by the winter of 2000. This system will run at 5 Hz for 10^5 shots between refurbishment. It will not meet the efficiency or durability requirements, but it will give us a vehicle to develop the emitter, hibachi, laser gas recirculator, and optics. In parallel with this effort we will develop the advanced pulsed power system. We anticipate that it will take three years to develop and will use technologies such as magnetic switches and solid state components that can meet the fusion energy requirements,. When completed it will be installed on Electra for a single integrated test.

B. KrF Physics:

We will perform basic and applied research to understand the physics of the electron beam propagation into the laser cell, and the kinetics and laser beam propagation inside the cell. This requires the development and testing of an electron beam propagation code to model the electron beam flow through the hibachi structure into the laser cell, an advanced kinetics code to model the e-beam pumped KrF laser media, and a laser beam propagation code to model the laser transport. All of these will be tested with experiments on the Nike 60cm amplifier, which will allow verification close to the scale of a power plant size system. The ultimate goal of this task is to verify that a KrF system can have the intrinsic efficiency of ~12% that is required for fusion energy. (Intrinsic efficiency is defined as the laser energy out divided by electron beam energy into the gas.)

C. Advanced Front End

We will need to develop an advanced front end. This is the initial, low energy stage of the laser system, and will be used to produce the required beam temporal and spatial characteristics: the ability to precisely control the laser temporal pulse shape, the ability to decrease the laser spot size as the target is compressed (called “zooming”), and the ability to produce flat top spatially uniform profiles on a scale of 4-6 mm diameter. One of the advantages of a KrF system is that these tasks can be carried at low energy in a single front end which then feeds all the laser beam lines. The technologies to meet these requirements exist but we must develop and integrate them specifically for this application.

D. Advanced Optics and Coatings

We will need to develop optical coatings that can survive the harsh environment of the laser cell: fluorine, HF, UV light, x-rays, and electrons. Currently the amplifier windows in Nike last several hundred shots. However, there are several promising multi-film techniques that may yield the lifetimes we require. In addition to the amplifier windows, we will also have to develop optics for the other laser components. We estimate that we will need optics that can survive laser fluences of 4-8 J/cm^2. Current technology is on the order of 2-3 J/cm^2, but numbers as high as 8 J/cm^2 have been achieved in small samples. We will mature this technology so that it can achieve the required damage threshold in power plant sized optics.

E. KrF Systems studies

We will use the results of our research to determine the optimal laser architecture for a power plant. By laser architecture, we mean the final amplifier size, the amplifier staging, the multiplexing/demultiplexing system, and the final optics layout. We will consider all components of the power plant in this study, including the chamber environment, final focussing elements, target injection system, and economics.

F. Phase I goals

We have compiled a list of goals and requirements that should be met before proceeding to Phase II. The laser rep-rate, efficiency, durability and cost requirements are derived from power plant studies, whereas the laser beam uniformity requirements are derived from the high gain target design. The chart shows what has been achieved, what we expect to achieve in Phase I and what is required for a fusion energy power plant. Parameters are listed in descending order of risk. "DD" is degree of difficulty, and is scaled as + / - / 0. with + being the easiest.

Parameter	**Now**	**Phase I goals**	**Fusion Energy Requirement**	**DD**
EFFICIENCY	**1.5%**	**6-7%**	**6-7%**	
Pulsed Power	63%(RHEPP)[2]	80%		+
Hibachi (foil support)	50%	80%		-
Ancillaries	N/A	95%[6]		0
Intrinsic (e-beam to laser)	7% Nike/ 14%[3]	12%[7]		-
Transport (laser to target)	75%	90%		+
DURABILITY (shots)[4]	**N/A**	**>10^5**	**3×10^8**	
Pulsed Power	3×10^7 (RHEPP)[5]	10^8		+
Cathode	10^8 (RHEPP)	10^8		+
Hibachi	100	>10^5		-
Amplifier Window	1000	>10^5		0
OPTICS DAMAGE THRESHOLD				
Lenses	3 J/cm^2	8 J/cm^2	8 J/cm^2	+
Mirrors	3 J/cm^2	8 J/cm^2	8 J/cm^2	+
COST[9]	N/A	study[6]	**$225/J (laser)[8]**	**+**
Pulsed power Cost	N/A	$5-10/J (e-beam)	$5.00/J (e-beam)[8]	+
REP-RATE	**.0005 Hz**	**5 Hz**	**5-10 Hz**	**+**
LASER UNIFORMITY				
Bandwidth	3.0 THz	2.0 THz	2.0 THz	++
Beam Quality, High Mode	0.2%	0.2%	0.2%	++
Beam Power Balance	N/A		2%	0

1. All parameters taken from Nike, unless otherwise indicated
2. RHEPP (Repetitive High Energy Pulsed Power, at Sandia National Laboratory)

3. 14% has been demonstrated on test cells. [Mandl et al, Fusion Technology 11, 542 (1987)]. A working amplifier will be 80-90% of this because of fill factor
4. Durability is defined as number of shots between major maintenance
5. Limited by lifetime of cables, which will not be used in laser system
6. Electra validates technology, cost & efficiency will be established with modeling based on Electra
7. Electra will achieve req'd efficiency, but will be too small to scale. Nike experiments will validate
8. 1999 dollars

The large KrF laser built at NRL (the site for Electra) has already met the beam uniformity requirements [2]. Moreover, because a KrF laser is driven by a pulse power system, it should also meet the rep-rate and cost requirements (although the latter must be demonstrated). The main challenges are to meet the requirements for efficiency and durability. These will be addressed thoroughly in Phase I.

III. PHASE II- THE IRE

The IRE will include a single beam line with the performance required for a fusion energy power plant (See the column in the Table, "Fusion Energy Requirements") The exact configuration of the beam line will be determined by the work in Phase I, but we would expect it to have 1-4 main amplifiers in the beam line, with each amplifier having an optical aperture in the meter class, and be pumped by opposing electron e-beams of energy 800 kV [5]. The electron beams would be produced by an array of cathodes, with each driven by their own independent pulsed power system in order to reduce the stored electrical energy and current handling requirements. These amplifiers would be driven by a single driver amp, which in turn would be driven by a front end. The total energy in each beam line would be between 50 and 150 kJ. (As a side note, a complete power plant laser is expected to have 20-50 such beam lines. But as they are all identical, it is only necessary to build one beam line to perform a credible full scale experiment.) The energy of the beam line would be distributed among 50 beams that are angularly multiplexed through the amplifier system. These beams would be grouped as clusters, with two or more clusters focussed on the injected target. The chamber would mimic the environment expected for a fusion system. The target would be a non-cryogenic surrogate, but could be configured to produce x-rays, neutrons or debris as required to investigate chamber wall and clearing issues. The exact requirements for the beam steering, beam uniformity and chamber environment will be determined by the other activities that will be carried out in parallel with the laser program.

IV. SUMMARY

We have taken a "systems approach" to develop a KrF laser for fusion energy. Our plan is part of an integrated science and technology program that includes all the components of a power plant: chamber, target physics, target fabrication, and target injection. We have formulated a two phase plan, based on requirements derived from the power plant studies and the high gain target design. The first phase will develop the required technologies, the second will build an Integrated Research Experiment (IRE). We define the IRE as an integrated repetitive demonstration that a power plant- class laser can be steered to illuminate a target injected into a reactor chamber environment, and it can do so with the uniformity and precision required for inertial fusion energy. Phase 1 has well defined goals that must be met before we can proceed to Phase II.

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5. M.W. McGeoch et al, Conceptual design of a 2 MJ KrF Laser Fusion Facility, *Fusion Technology*, 32, 610 1997.