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Fusion Electra: A Krypton Fluoride Laser for Fusion Energy

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Electra is a Krypton Fluoride (KrF) laser to develop the science and technology for Inertial Fusion Energy. The objective is to develop the technologies that can meet the IFE requirements for beam quality, durability, and efficiency. Electra will use double-sided electron-beam pumping, run at 5 Hz, and have a laser output of 400-700 Joules. We will focus on technologies that can be scalable to the 50-150 kJ energy needed for a full-size fusion power plant beam line and are projected to meet the economic requirements for fusion power. Electra is a multifaceted, multi-disciplinary program that will perform the research needed to develop the individual laser components and then combine the components into an integrated system. These components are: the pulsed power system; the electron beam emitter; the pressure foil structure; the recirculator to cool and quiet the laser gas; and long life optical windows. We have built a first generation pulsed power system which runs continuously in 100,000 shot runs at 5 Hz at full energy. This five-hour run is more than adequate to start developing the laser components. To date we have evaluated a large number of cathode materials, have developed a first generation hibachi design, performed experiments and modeling of electron beam transport and stability, developed models for the electron beam deposition and KrF kinetics, started component development for an advanced pulsed power system, and are developing long life optical coatings.

1. Introduction

Direct drive with krypton fluoride (KrF) lasers is an attractive approach to fusion energy: KrF lasers have outstanding beam spatial uniformity, which reduces the seed for hydrodynamic instabilities; they have an inherent short wavelength (248 nm) that increases the rocket efficiency and raises the threshold for deleterious laser-plasma instabilities; and they have the capability for "zooming" the spot size to follow an imploding pellet and thereby increase efficiency. Numerical 1-D simulations have shown that a target driven by a KrF laser can have a gain above 125 [1,2], which is ample for a fusion system. Simulations of the pellet burn in 2-D and 3-D are also being conducted using commercial and homegrown multiprocessor computers. These simulations will establish the target and laser criteria for current pellet designs and help develop more advanced designs. The simulations and their underlying codes are benchmarked with experiments on the Nike KrF laser at NRL. Nike has demonstrated that a large (3-5 kJ) KrF laser can be built and can produce highly uniform target illumination [3]. The Nike laser generates a beam with the proper pulse shape required for fusion energy, and ablatively accelerates planar targets with nearly the same composition (low density foam wicked with cryogenically cooled liquid D_2) and close to the same areal mass that are required for a high gain system. In addition to these laser-target issues, the Sombrero Power Plant study showed a KrF based system could lead to an economically attractive power plant [4]. The purpose of the Electra program described here is develop the technologies that can meet the fusion energy requirements for repetition rate, efficiency, durability, and cost.

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2. The Electra Laser Program

Electra will be a 400-700 J, 30 cm aperture, 5 Hz rep-rate facility. It will be 1-2% of the energy of a power plant size laser beam line, but because of the modular nature of the laser, that is large enough for the developed technologies to be directly scalable to a full size system. The requirements for a fusion power plant laser are based on both power plant studies and on our high gain target designs. A summary of the requirements is shown in Table I.

Here the durability is defined as the shots between major maintenance, and the cost is given in 2001 dollars.

Table I Fusion Energy Requirements for a KrF laser

Parameter	**Qty**
System efficiency	6-7%
Rep-Rate	5 Hz
Durability (shots)	3×10^8
Lifetime (shots)	10^{10}
Cost of entire laser	$250/J(laser)
Cost of pulsed power	$5-10.00/J(e-beam)
Laser Beam uniformity	< 0.2%
Optical Bandwidth	2-3 THz
Laser Beam Power balance	<2%
Laser Energy-total	1.6-2.4 MJ
Laser Energy (per beam line)	50-150 kJ

The main amplifier of Electra will be pumped with two 30 cm x 100 cm electron beams, each with $V = 500$ kV, $I = 110$ kA, and pulse duration $\tau = 100$ 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 [5]: a durable, efficient, and cost effective pulsed power system; a durable electron beam emitter; a long life, transparent pressure foil structure (that isolates the laser cell from the electron beam diode the so-called "hibachi"); a recirculator to cool and quiet the laser gas between shots; and long life optical windows.

It will take several years to develop an advanced pulsed power system that can meet all the IFE requirements for durability, efficiency, and cost. Fundamental research and development must be carried out to realize the technology needed to build an appropriate system. However, we do not want to wait until that system is operational before we can start developing the other laser components. Therefore we have developed and built a First Generation Pulsed Power System that is an extrapolation of existing technology [6]. While the technology used in this system will not meet the efficiency or durability requirements, it does have the required output and repetition rate. This system uses

Figure 1. The Electra Laser Facility

a capacitor/step-up transformer prime power system that pulse charges a pair of coaxial, water dielectric, pulse forming lines. The energy in the lines is then switched into the electron beam diode load using laser-triggered spark gaps. The First Generation System can run at 5 Hz for 10^5 shots between refurbishment. (Refurbishment is a simple manner of replacing two pairs of electrodes.) This five hour run is unprecedented for a pulsed power system of this size (50 kW @ 500 kV) and is more than ample to develop the required laser components. We have coupled this pulsed power system to the laser development facility, including the magnets, laser cell, both diode boxes and the gas recirculator. A photo of the Electra facility (without the gas recirculator) is shown in Figure 1. Note that there are two identical systems on either side of the laser cell.

Regarding the final pulsed power system, we have performed studies of several approaches that have the potential to meet the IFE requirements. The two most promising are based on laser gated solid state switches. In this approach a small diode laser integrated directly with a silicon semiconductor PNPN switch, and is used to photonically flood the junctions and entire volume of the device. This causes the whole switch to turn on very rapidly and allows it to pass a rapidly rising current. In one manifestation the switch operates at 40 kV and is used in an ultra fast Marx arrangement. In another, albeit more difficult approach, the switch operates at up to 1 MV and is used to switch out a water dielectric pulse forming line or Blumlein line This is a direct replacement for the relatively short-lived high voltage spark gap gas switches such as those used in the present system. Our systems modeling suggests this approach can lead to overall efficiencies of up to 87%. Already a prototype switch that validates the concept has been made operational.

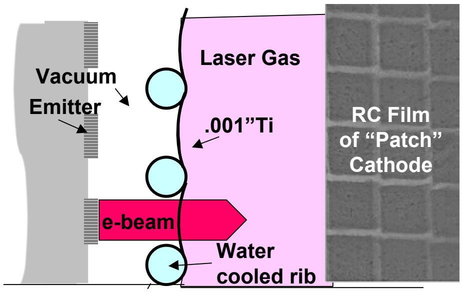

Figure 2: Water Cooled Hibachi Concept

It is obvious that to meet the efficiency requirements, we need to "pattern the beam" so that it will miss the ribs of the hibachi structure. Our baseline design is to make the hibachi supports out of thick wall tubing that contains flowing water for coolant. A depiction is shown in Figure 2. Our preliminary CFD (Computational Fluid Dynamic) analysis shows that this type of arrangement can remove enough of the heat from the foil to keep the system at a reasonable temperature, given our measured foil energy deposition, *if* the ribs are spaced relatively close together (1.2 cm gap). However the close spacing makes propagating the beam through the gaps difficult, particularly considering that the applied axial magnetic field causes the beam to rotate as it propagates . A more promising approach is to space the ribs further apart and induce turbulence in the laser gas between shots to provide foil cooling. We have also demonstrated that we can produce an electron beam in a pattern that is consistent with this concept. We have made the beam in both 1 cm wide by 30 cm high strips and 3 cm x 3 cm patches. The latter is shown in the right hand side of Figure 2, which shows a radiachromic (RC) film image of the electron beam at the anode. This segmenting may also be needed to quench the "transit time instability" discussed below.

We are performing basic and applied research to understand the physics of the electron beam pumped KrF lasers. This includes the development of three codes: 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. The ultimate goal of this task is to develop a predictive capability for large electron beam pumped amplifiers, and to possibly increase the intrinsic efficiency of a KrF system to above the ~12% that is presently observed [7]. (Intrinsic efficiency is defined as the laser energy out divided by electron beam energy into the gas.) All of these codes will be tested with experiments on both Electra and the Nike 60cm amplifier. The latter will allow verification close to the scale of a power plant size system. At the present the three codes are being developed separately. They will be combined into a single monolithic code when they are more mature.

Our beam propagation code models the transport of the electron beam in the diode, through the hibachi structure and into the laser gas. This is a Particle in Cell (PIC) Code that includes scattering in the hibachi foil, back scattering from the laser gas into the diode, and re-injection of the electrons. We have used this model to predict that the water-cooled tube hibachi design described above will allow up to 79% energy of the electron beam energy to be deposited into the laser gas. The code has also been used to model experiments on Nike, which established that large area electron beams are subject to a transit time instability [8]. This instability imparts both a transverse and longitudinal energy spread to the beam, and hence is a loss mechanism that must be eliminated. Fortunately, our theory and particle simulations show that the instability can be eliminated by slotting the cathode and loading the slots with resistive elements. This slotted cathode is consistent with the hibachi designs quoted above, where the electron beam is segmented to miss the hibachi ribs.

In the arena of the KrF kinetics, we are developing a computer code to model the temporal and spatial behavior of e-beam pumped KrF laser amplifiers. The physics is divided into several components: (1) kinetics of the KrF plasma medium, (2) amplification of the seed laser beam, and (3) incoherent propagation of the Amplified Spontaneous Emission (ASE). The kinetics code already can predict the results of two very different KrF systems, one a double pass, relatively low pump power system, another a single pass high pump power system. This is shown in Figure 3.

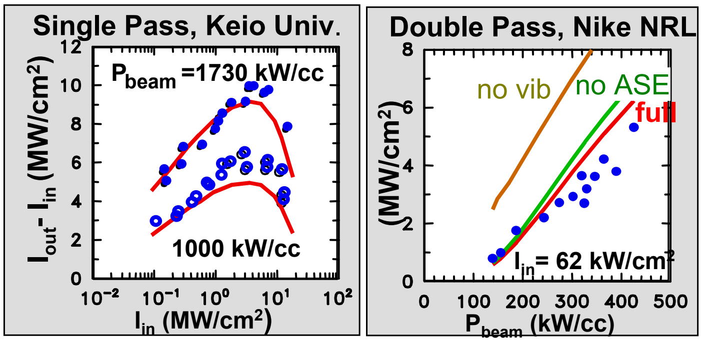

Figure 3: KrF Kinetics Modeling

The gas in the laser cell must be cool and quiescent on each shot to ensure that the amplified laser beam is very uniform. A preliminary design shows that a system can be made that meets our power and smoothing requirements. Based on this design, we have produced a first generation recirculator for Electra.

3. The Next Step

Although we discuss only the KrF laser program in this paper, 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, final optics, materials, and ultimately, the cost of energy. If this entire program is successful in meeting its goals, the next step would be to build 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 and will be an integrated repetitive demonstration that a laser beam can be steered to illuminate a target injected into a reactor chamber environment, with the repetition rate, uniformity and precision required for inertial fusion energy. The laser in the IRE 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 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.

4. Summary

Electra will be a 400-700 J Electron beam pumped KrF laser that will develop the technologies for fusion energy. It is part of a larger integrated program to address all the IFE components as a coherent system.

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