THE ELECTRA KRF LASER*

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Abstract

Electra is a repetitively pulsed, electron beam pumped Krypton Fluoride (KrF) laser that will develop the technologies that can meet the Inertial Fusion Energy (IFE) requirements for durability, efficiency, and cost. The components that need to be developed are: a durable and efficient pulsed power system; a durable electron emitter; a long life, transparent pressure foil structure (hibachi); a laser gas recirculator; and long life optical windows. The technologies developed on Electra will be directly scalable to a full size fusion power plant beam line. This paper gives an overview of the Electra program, and then concentrates on the most recent research results of electron beam deposition through the hibachi into the laser cell.

I. INTRODUCTION

Direct drive with 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. The fusion energy requirements for a KrF IFE laser are based on the Sombrero power plant studies [1] and on high gain target designs [2,3]. A summary of the main IFE requirements is shown in Table 1. Beam quality and optical bandwidth requirements are less difficult to meet, while system efficiency, durability and lifetime are the most demanding requirements.

II. THE ELECTRA LASER PROGRAM

Electra is a KrF laser facility with a repetition rate of 5 Hz and a laser energy of up to 700 J per pulse. The key components of the Electra main amplifier are shown in Fig. 1. They include two pulsed power systems, 30x100 cm^2 cathodes, pressure foil support structures (hibachi); a laser cell with a double sided e-beam pumped cross-section of 30x30 cm^2; a laser gas recirculator, laser cell windows, and output optics.

Table 1. Fusion energy requirements for a KrF IFE laser.

Parameters	IFE
Beam quality (high mode)	0.2%
Beam quality (low mode)	2%
Optical bandwidth	1-2 THz
Beam Power Balance	2%
Rep-Rate	5 Hz
Laser Energy (beam line)	40-100 kJ
Laser Energy (total)	1.7-4 MJ
Cost of pulsed power(1)	< \$10/J(e-beam)
Cost of entire laser(1)	\$225/J(laser)
System efficiency	6-7%
Durability (shots)(2)	3×10^8
Lifetime (shots)	10^{10}

(1) 2002 $. Sombrero (1992) gave $4.00/J (pulsed power) and $180/J (entire laser)
(2) Shots between major maintenance (2 years)

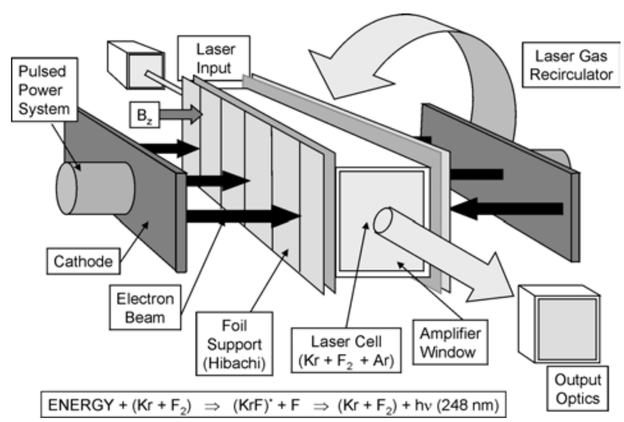

Figure 1. The main components of an electron beam pumped KrF laser.

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A. Pulsed Power Systems

A "first generation" pulsed power system has been designed and deployed on which the laser component technologies are being develop. Each pulsed power system consists of a capacitor bank that feeds the primary side of a step-up autotransformer. The secondary side charges a pair of coaxial, water dielectric, pulse forming lines. The energy in the lines is then switched into the vacuum diode (load) using laser-triggered spark gaps. The system operates at 400-550 kV, 70-110 kA, and with a 100 ns flat-top pulse duration. Figure 2 shows typical voltage and electron beam current density waveforms. The pulsed power system can run at 5 Hz continuously for 10^5 shots without refurbishment. (Refurbishment is a simple matter of replacing two pairs of electrodes.) A detailed description of the system is given in reference [4]. Although this first generation system does not meet the IFE requirements for durability and efficiency (see Table 1), it is an excellent test bed for developing laser components.

An advanced pulsed power system that can meet all the IFE requirements for durability, efficiency, and cost is currently under development [5]. It is based on an ultra fast Marx with laser gated semiconductor switches, a single stage magnetic compressor, and a transit time isolator. Present design parameters are 750 kV, 180 kA, with a 40 ns risetime, 600 ns flat-top, and 40 ns fall time. System models predict a flat-top e-beam energy over wall plug efficiency of 85%. To ensure its durability, end of life component testing on capacitors, solid state switches, as well as liquid breakdown studies in large area, repetitively pulsed system are being carried out [6].

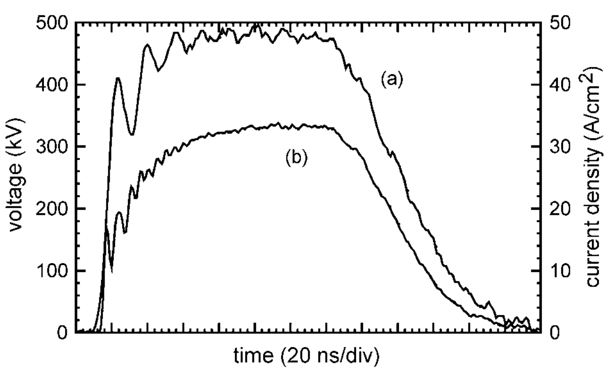

Figure 2. Typical voltage and current density waveforms for velvet cathode experiments. (a) diode voltage and (b) current density waveform near the beam center, with an A-K gap of 5.2 cm.

B. Cathode

One of the key challenges for a long-lived KrF laser is the development of a durable cathode. The Electra program is evaluating a number of cathode options that can meet the requirements for risetime (< 40 ns), uniformity (< 10%), impedance collapse (< 1 cm/μs), and durability (> 3×10^8 shots). Double density velvet cloth, made by Youngdo Velvet, product # AW-1100, meets the first three requirements, but is not expected to have the required durability. To date, seventeen different cathodes have been evaluated, and more details on these cathode studies are found in reference [7].

C. Electron Beam Transport and Deposition

Another key challenge is the development of a hibachi that allows reliable and efficient injection of the electron beam into the laser gas. To achieve an overall laser system efficiency of 6-7%, the IFE system requires a ratio of energy deposited into the laser cell over flat-top diode e-beam energy of at least 80% for a 750 keV electron beam (see Table 2).

High energy deposition efficiency was achieved with two innovations: 1) eliminating the anode foil on the diode side of the hibachi structure, and 2) patterning the electron emitter into strips so the beam "misses" the hibachi ribs. While these are conceptually simple, they are difficult in practice: Eliminating the anode results in highly non-uniform electric fields, and the beam rotates and shears due to its interaction with the applied axial magnetic field of 1.4 kG that is used to guide the e-beam into the laser cell. Figure 3 shows the basic configuration of the diode. The hibachi stainless steel ribs are 5 mm in width, 28 mm deep, and they are spaced 4 cm apart. They support a Ti pressure foil that is 25 or 50 μm thick. For deposition measurements, the laser cell is filled with Krypton or a Krypton/Argon mixture at pressures ranging from 1 to 2 atm. Advantages of a design without an anode foil (see Fig. 3) are increased hibachi durability and mitigated anode foil e-beam absorption and scattering losses. The experimental data given below indicate that the hibachi ribs provide an adequate "electrically flat anode" for electron beam generation and propagation.

Table 2. Efficiency allocation for an IFE KrF laser system.

System component	Efficiency
Pulsed power (flat-top e-beam energy over wall plug)	85%
Hibachi (energy deposited into laser cell over flat-top e-beam energy)	> 80%
Intrinsic (KrF kinetics)	10-12%
Ancillaries	95%
Optical Train	95%
Total efficiency	6-7%

All experimental energy deposition results have been obtained with velvet cloth cathodes. The e-beam deposition efficiency at 500 kV, with a 50 μm thick Ti pressure foil, and a laser cell gas of Krypton at 1.2 atm has been measured for two types of cathodes: (a) a monolithic 27 x 97 cm^2 cathode at an A-K gap of 42 mm and (b) a strip cathode; 24 strips, each 25 mm x 27 cm, at an A-K gap of 37.5 mm. The deposition efficiencies for both cathodes are shown in Table 3. The deposited energy has been obtained from a Baratron that measures the pressure rise in the laser cell. The measurements include the flat-top portion of the e-beam pulse as well as rise and fall times. 1-D Tiger simulations showed that with a 50 μm thick Ti pressure foil the rise and fall of the beam contribute 25% and the flat-top 75% of the energy in the laser cell. From this simulation, the deposition efficiency for the flat-top portion of the e-beam pulse has been estimated. In addition, the experimental data is compared with 1-D simulations that do not include the hibachi ribs, e.g., by modeling only the pressure foil and the laser gas. In this case the code predicts the theoretical deposition efficiency limit without e-beam losses due to the hibachi.

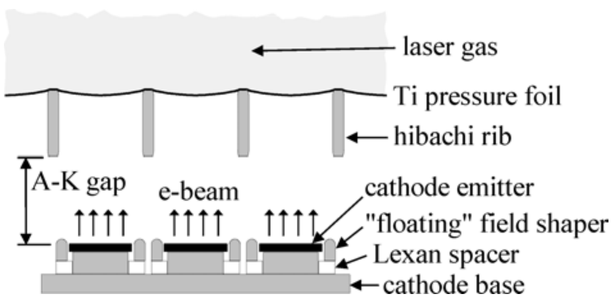

Figure 3. Diode configuration with 28 mm deep hibachi and 25 mm wide strip cathode with "floating" field shapers. The A-K gap is measured from the cathode emitter surface to the hibachi front surface.

Table 3. E-beam energy deposition efficiency at 500 kV, 1.2 atm of Kr, and a 50 μm thick Ti pressure foil.

	Efficiency for the entire pulse	Efficiency for flat-top portion
Monolithic cathode	47%	53%
Strip cathode	62%	67%
Simulations without hibachi ribs	67%	72%

It is obvious that the energy deposition efficiency is increased by segmenting the electron beam so that it will miss the hibachi ribs. In addition, the cathode strips are "counter-rotated" so that the beam will be propagating parallel to the ribs when it gets to the hibachi. The cathode strips are rotated by 6°, and the strip-to-strip spacing is increased by 0.5 mm compared to the hibachi rib-to-rib spacing to compensate for beam pinching.

In order to eliminate the e-beam halos of each strip cathode, a new concept of a "floating" electric field [8] shaper has been investigated. This field shaper is electrically isolated from the cathode, and its capacitance and charge are minimized. Therefore, a floating field shaper should not emit significant currents unless the cathode plasma expands and electrically connects the field shaper to the cathode. This differs from the commonly used technique of coating a field shaper, which is in direct contact with the cathode base, with an insulating layer to prevent electron emission [9]. The floating field shaper concept has been tested under repetitive operation at 1 pulse per second for 3000 shots at 500 kV, with an A-K gap of 42 mm, and 160 ns FWHM pulse duration. The field shaper did not show any visible surface damage.

Table 3 shows that the energy deposition efficiency during the flat-top portion of the pulse is 67% while 1-D simulations without hibachi ribs (e.g., simulation considers e-beam, 2 mil Ti foil, and laser gas only) predict a deposition efficiency of 72%. These results show that the segmented e-beam propagates efficiently between the hibachi ribs with only minor losses, thus, patterning the electron beam imitates operation of a nearly "rib-less hibachi".

The effects of diode voltage vs. Ti pressure foil thickness are summarized in Table 4. For all cases, the strip cathode was counter-rotated by 6° and had a strip-to-strip spacing of 40.5 mm. To achieve the desired diode voltages the A-K gap was adjusted to 28.5 mm and 37.5 mm for the 400 kV and 500 kV cases, respectively.

Table 4. Flat-top e-beam energy deposition efficiency with a strip cathode at 400-500 kV and 25-50 μm thick Ti pressure foils.

Diode voltage	Flat-top efficiency with 50 μm thick Ti pressure foil	Flat-top efficiency with 25 μm thick Ti pressure foil
400 kV	57%(1)	71%(2)
500 kV	67%(3)	75%(4)

(1) 1 atm. at 40% Kr and 60% Ar
(2) 1 atm. at 60% Kr and 40% Ar
(3) 1.2 atm. at 100% Kr
(4) 1.3 atm. at 100% Kr

The energy deposition efficiency significantly increases with the 25 μm thick Ti pressure foil compared to the 50 μm thick foil. Note that the minimum gas pressure to stop the e-beam in the laser cell changes for the various cases as indicated by the footnotes of Table 4. The continuous slowing down approximation (CSDA) [10] predicts that 25 and 50 μm thick Ti foils require a minimum passing energy of 70 and 105 keV, respectively.

3-D LSP [11] simulations, which include the actual diode geometry, external magnetic field, hibachi ribs, and backscattering, showed that the energy deposition efficiency is 74% for a 500 keV beam and a 25 μm thick Ti pressure foil. This agrees well with the experimental observation of 75%.

To achieve even higher deposition efficiencies, a new hibachi with shallower ribs (13 mm instead of 28 mm) is currently under construction. It should create a more uniform electric field at the anode, and thus, minimize e-beam spreading losses. Preliminary simulations showed that the ultimate goal of >80% hibachi efficiency is achievable in a full-scale (750 keV) system.

D. Laser Cell and Gas Recirculator

The laser gas must be cool and quiescent on each shot to ensure a very uniform amplified laser beam. Of particular importance is the elimination of short scale-length, ordered temperature variations perpendicular to the aperture. A recirculator has been designed for Electra that should achieve the required uniformity and cooling. This design includes louvers in the laser cell that can be rotated to temporarily trip the normally quiescent gas flow to turbulence, and direct the gas flow to the pressure foils. Computational fluid dynamic analysis showed that cycling the louvers for the first 60 msec after each shot can keep the pressure foil to below 650° F (340°C), yet allow ample time for the gas to return to a quiescent state before the next shot 140 msec later (allowing a laser repetition rate of 5 Hz). A recirculator for Electra's main amplifier is currently under construction, and it will be tested in early 2003.

E. Laser Windows and Optics

The laser cell windows require high quality anti-reflection coating (AR) interior to the laser cell that need to survive the rather harsh environment of UV, fluorine, HF, electrons, and x-rays. AR coated fused silica samples have been obtained from a number of sources and are undergoing exposure tests at a level of 5 % fluorine, an order of magnitude greater than present in the laser gases. Provisions are made for simultaneous exposure to both fluorine gas and laser radiation at 10 Hz. The test capability will be extended soon to 50 Hz with the installation of a new commercial KrF laser.

Optical damage levels are determined by observation using a Zygo 3D microscope, as well as reflectivity and transmission measurements. A "home-grown" coating of MgF2/alumina on a 2.5 cm diameter sample of fused silica has shown promise of meeting the requirements of high optical transmission (0.8% loss at 248 nm), laser damage threshold (> 1.5 J/cm^2 at 32 nsec pulse) plus F_2 and HF resistance Further evaluations with larger scale samples are planned.

F. KrF Kinetics

In addition to the experimental research on components for a rep-rated laser facility, the Electra program also includes the development of a simulation code, Orestes, for the KrF kinetics within the amplifier. The objective is to provide reliable predictions for the laser output as a function of electron beam properties. Orestes is a first principles physics code that couples various processes in a self-consistent manner. A Boltzmann model is used to calculate the non-Maxwellian electron energy distribution function resulting from the e-beam deposition in the gas. This function specifies the ionization and excitation rates which subsequently initiate the plasma chemistry [12,13]. The kinetics of 23 species subject to >100 reactions as well as the gas and electron internal energy are followed with 1-D spatial resolution of the amplifier along the lasing axis. While ideally the deposition is uniform, the gain changes along the axis due to saturation of the lasing light. The exponential amplification by stimulated emission of the input laser is accurately followed in a single or double pass design using the method of characteristics. Amplification of spontaneous emission (ASE) leads to incoherent propagation and detracts from the amplifier efficiency. The time-dependent ASE is followed in 3-D using hundreds of discrete ordinates to account for wall reflections and angular anisotropy. A detailed treatment of the vibrational levels in the KrF molecule specify the stimulated emission cross section for lasing and ASE photons.

Validation of Orestes is based on comparison of the calculated gain, saturation intensity, and laser output with existing experimental data from Nike [14,15] and a facility at Keio University [16]. The data covers a broad range of conditions from 200 kW/cc to 1.7 MW/cc beam power deposition, 10% to ~100% Kr composition, and an input laser intensity from 62 kW/cm^2 to 10 MW/cm^2. The robust applications of the Orestes simulations provide confidence of the required predictive capability for a systems design code. Analysis of Electra, including stopping conditions for the electron beam in the gas, indicates that a 10 J laser input with 800 kW/cc beam power deposition at 500 keV and a 99.5%/0.5% Kr/F_2 composition at 1.2 atm will produce nearly 500 J of laser output per pulse. The output laser energy can be increased to 700 J per pulse for a 1 atm. mixture of 25%/0.5%/74.5% Kr/F_2/Ar while maintaining the above beam power deposition.

III. FUTURE DIRECTIONS

The Electra KrF laser program described in this paper is part of a larger, broad based integrated program that looks at all major issues for Laser Fusion Energy. They include the driver, target gain, chamber, target fabrication, target injection, final optics, material, and ultimately, the cost of energy. If the entire program is successful in meeting its goals, the next step would be to build an Integrated Research Experiment (IRE). Such a program should address the key enabling technologies for a laser driven fusion power plant. The IRE will consist of a laser beam line, steering mirrors, a target injector, and chamber. These components will be integrated into a system to demonstrate 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 a laser fusion power plant. Initial scaling calculations with the Orestes code indicate that the intrinsic efficiency of an IRE amplifier is consistent with values given in Table 2. The laser energy and average power on target would be sufficient that this facility could be used for component research, such as the examination of chamber clearing issues and investigation of chamber wall materials to x-ray pulses.

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