Krypton Fluoride Laser Development for Inertial Fusion Energy

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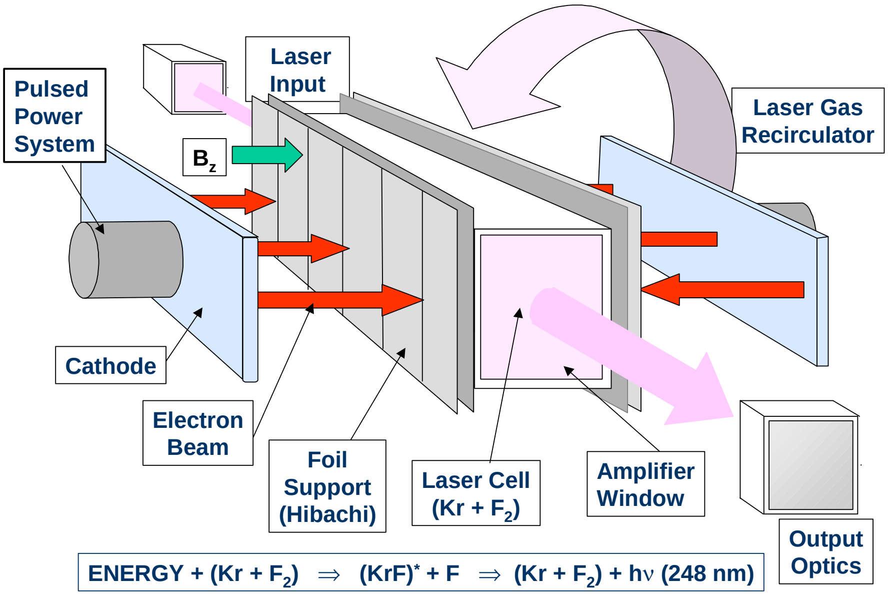
1 . Introduction

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. Our 1-D numerical 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. We are also conducting simulations of pellet burn in 2-D and 3-D using commercial and homegrown multiprocessor computers. These simulations will allow us to establish target and laser criteria for current pellet designs and help us develop more advanced designs that are even more resistant to hydrodynamic instabilities. 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]. Nike ablatively accelerates planar targets that have close to the pulse shape and areal mass that are required in a high gain system. Moreover, the targets are composed of similar materials (low density foam wicked with cryogenically cooled liquid D_2) as in a high gain target. 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]. In order to fully evaluate this approach to fusion energy, we need to establish if a krypton fluoride laser can meet the requirements for inertial fusion energy. That is the purpose of the Electra program at the Naval Research Laboratory.

2. The Electra Laser Program

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. These requirements are based on both power plant studies and on our high gain target designs. Electra will be 1-2% of the energy of a power plant size laser beam line, but it will be large enough that the technologies will be directly scalable to a full size system. 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: 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. These are shown schematically in Figure 1. Components that can meet these requirements have been identified [5]. Many have already been developed separately, but not necessarily in a parameter range suitable for fusion energy [5]. Our plan is to develop these components specifically for fusion in a single integrated laser facility.

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



We will build two complete pulsed power systems for Electra. 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 develop the components necessary 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 [6] that is only a modest extrapolation of existing technology. This system uses 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 (25 kW @ 500 keV) and is more than ample to develop the required laser components. A photo of the Electra facility is shown in Figure 2.

Figure 2. The Electra Laser Facility

The second pulsed power system will be the one that can meet the IFE requirements for durability, efficiency and cost. We have identified three systems that have the potential to meet these requirements. The first is based on magnetic switches using saturable inductors. This is a low risk approach with respect to existing technology, but the system would be marginal in meeting the cost and efficiency requirements. Accordingly, we have evaluated two more systems that have greater promise, but require more research and development. Both are based on laser gated solid state switches. In this approach a small diode laser is used to flood the junction and volume of a semiconductor switch. This causes the entire 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. This is a direct replacement for the relatively short-lived gas switch in the present system, and can lead to overall efficiencies of up to 87%. Currently we are performing the advanced component research to develop both types of laser triggered switches as well as some components in the magnetic compressor system. We will pick the best approach then use it as the basis for a system that will be integrated into Electra.

One of the key challenges for a long-lived KrF laser system is the development of a cathode and hibachi (foil support structure) that allows the electron beam to efficiently and reliably be injected into the gas. We are evaluating a number of cathode options that can meet the requirements for risetime (< 40 nsec), uniformity (< 10%), impedance collapse (< 1 cm/μsec), and durability (> 3 x 10^8 shots.) Ultra fine double velvet cloth meets the first three requirements, but is not expected to have the required durability. To date we have evaluated seventeen different cathodes. The most promising are cathodes based on flocked carbon fiber and on a metal-dielectric structure.

It is obvious that to meet the efficiency requirements, we need to develop an electron beam emitter that can produce a "patterned beam" that can miss the ribs of the hibachi structure. Our baseline design is to make the hibachi supports out of thin wall tubing that contains flowing water for coolant. A depiction of this is shown in Figure 3.

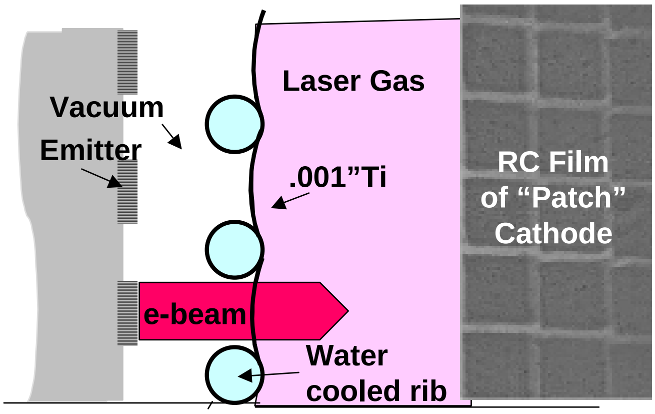


Figure 3: Water Cooled rib Hibachi Concept

Our preliminary computational analysis shows that this type of arrangement can remove enough of the heat from the foil to keep the system at a reasonable temperature. 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 3, 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 use an applied axial magnetic field to guide the beam into the laser gas and prevent it from pinching. The interaction of this applied field and the current of the beam causes the beam to rotate, which can clearly be seen in the RC film image. This must be taken into account in designing the cathode/hibachi.

We are also performing basic and applied research to understand the physics of the electron beam pumped KrF lasers. We are developing and testing 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, backscattering 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. This is on Electra with an electron beam voltage of 500 keV. In a full scale system operating at 750 keV the expected deposition is 85%. This is more than ample to meet the transport efficiency requirements.

We have established, through experiments, simulations and theory, that large area electron beams are subject to a transit time instability [8]. The electron beam is modulated at a frequency of 2.5 GHz and the resulting axial momentum spread results in a large fraction of the beam being either lost in the foil, or completely traversing the cell. In addition, the electrons can lose 10-20% of their energy to the electromagnetic field, which, in turn, feeds the instability. The instability also imparts a transverse velocity to the beam which results in a significant fraction of the beam lost to the hibachi ribs. Obviously this instability is a loss mechanism that must be eliminated. Fortunately, our theory and particle simulations show that the instability can be mitigated, and possibly even eliminated, by slotting the cathode and loading the slots with resistive elements. This effectively turns the cathode-anode into a slow wave structure that damps the RF oscillations. Simulations of the resistively loaded slots showed no sign of any instability. This result was also obtained when the applied voltage was modulated 10% by either white noise or by a 2.5 GHz perturbation. This slotted cathode is consistent with the hibachi designs quoted above, where the electron beam is segmented to miss the hibachi support structure 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 plasma is divided into 20 or more zones along the axial lasing direction, with uniform e-beam energy deposition throughout the plasma. This can readily be generalized to full 3-D resolution in the future. The kinetics model follows 23 species, including electrons, for a Kr/Ar/F_2 mixture with 116 reactions. The transport and amplification of the input laser beam is solved using the method of characteristics. This is a stable and accurate technique for handling the exponential gain, and it treats double pass operation with a minimum of additional complication. To date this code can predict the observed output of the Nike 60cm amplifier, as well as with other KrF systems operating in very different regimes. This is the first time a KrF kinetics codes has been able to model a wide range of KrF systems, and gives us confidence that we may be able to have a predictive capability in hand.

The gas in the laser cell must be cool and quiescent on each shot to ensure that the amplified laser beam is very uniform. Of particular importance is the elimination of short scale-length, ordered temperature variations perpendicular to the aperture. The EMRLD laser successfully addressed this problem (EMRLD was an electron beam pumped XeF laser developed by AVCO Textron for the Air Force). In EMRLD the gas in the laser cell was circulated through a flow loop that contained a series of mixing plates, diffusers, and heat exchangers. This enabled the EMRLD laser to faithfully amplify a 1.3 x diffraction limited (XDL) laser beam [9]. This is far better than the 5 XDL that is required for Electra. The shot rate was 100 Hz, and the (supply-limited) duration was 10 seconds. The largest aperture one would consider for a large (50-150 kJ) laser is about 200 cm. Thus, the EMRLD results suggests this technology could readily scale to 5 Hz. A preliminary design shows that it is indeed feasible to make such as system, and that it will meet our power and smoothing requirements [10]. Based on this design, we have produced a first generation recirculator for Electra that will test the baseline flow, the acoustic suppression and the heat removal. The system has been delivered and is undergoing final modifications before installation on Electra.

There are several other components to the Electra Program. Among these is the development of an advanced front end for Electra. This is the initial, low energy stage of the laser system. It will be used to produce the beam temporal and spatial characteristics that is required by the high gain target design; i.e. 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. The front end implements the Induced Spatial Incoherence (ISI) beam smoothing that allows KrF lasers to achieve highly uniform and controlled illumination of targets at high intensity. This capability for uniform target illumination is the single most compelling reason to develop high-energy high-repetition rate KrF laser technology. Another advantage 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. Most likely the front end will be some type of electron beam system, as discharge pumped lasers alone cannot produce the needed longer timescale pulses or pump larger apertures.

We also are developing optical coatings for the Electra Amplifier. These need to survive the rather harsh laser cell environment of UV, fluorine, HF, electrons and x-rays. We are using an Ion Beam Assisted Deposition (IBAD) system deposit various coatings of hafnia, magnesium fluoride, or alumina, onto a suitable substrate (usually fused silica). These are being tested in a controlled environment test cell that mimics the laser cell environment. The coated samples are checked for transmission, uniformity and index of refraction (i.e. n, and k) using a Photospectrometer, an HeNe Laser Probe, and a fiber optic spectrometer. We are also characterizing the surfaces using electron, optical, or atomic force microscopy. The coatings that that are resistant to chemical corrosion and have a high enough transmission will be tested for durability to high power laser light. The ultimate goal is a damage threshold of 5 Joules/cm^2. Finally, we will test candidate materials in the Nike 60 cm amplifier, and evaluate their behavior in an actual laser cell environment to determine the effect of x-rays and high energy electrons.

We will use the results of our research to determine the optimal laser architecture for a large (1.2 to 2.4 MJ) laser system. 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.

We have compiled a list of goals and requirements that should be met before proceeding to a second phase of the program. These are listed in Table I. 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. Table I shows what has been achieved, what we expect to achieve during the Electra program, 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.

3. The Integrated Research Experiment-- 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, and ultimately, the cost of energy. If the Electra program, as well as these other research areas are successful

Table I: The Goals for the Electra Laser Program

Parameter	Now	Phase I goals	Fusion Energy Requirement	DD
EFFICIENCY	1.5%	6-7%	6-7%	
Pulsed Power	63%(RHEPP)[b]	80%		+
Hibachi (foil support)	50%	80%		-
Ancillaries	N/A	95%[f]		0
Intrinsic (e-beam to laser)	7% Nike/ 14%[c]	12%[g]		+
Transport (laser to target)	75%	90%		+
DURABILITY (shots)[d]	N/A	$>10^5$	3×10^8	
Pulsed Power	3×10^7 (RHEPP)[e]	10^8		+
Cathode	10^8 (RHEPP)	10^8		0
Hibachi	100	$>10^5$		-
Amplifier Window	1000	$>10^5$		0
OPTICS DAMAGE THRESHOLD				
Mirrors at 5 Hz	> 5 J/cm^2 (5 cm optics)	5 J/cm^2 (20 cm optics)	5 J/cm^2 (100cm optics) 5-8 J/cm^2 (20cm optics)	0
COST[h]	N/A	study[f]	\$225/J (laser)[h]	+
Pulsed power Cost	N/A	\$5-10/J (e-beam)	\$5.00/J (e-beam)[h]	+
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

a. All parameters taken from Nike, unless otherwise indicated
b. Repetitive High Energy Pulsed Power, at Sandia National Laboratory [11]
c. 14% has been demonstrated on test cells. [7]. A working amplifier will be 80-90% of this because of fill factor
d. Durability is defined as number of shots between major maintenance
e. Limited by lifetime of cables, which will not be used in laser system
f. Electra validates technology, cost & efficiency will be established with modeling based on Electra
g. Electra will achieve required efficiency, but will be too small to scale. Nike experiments will validate
h. 1999 dollars

in meeting their 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. The entire system will run at 5 Hz. 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.

4. References

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