KrF Laser Development for Fusion Energy[*)]

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The United States Naval Research Laboratory is developing an electron beam pumped krypton fluoride laser technology for a direct drive inertial fusion energy power plant. The repetitively pulsed krypton fluoride laser technology being developed meets the fusion energy requirements for laser beam quality, wavelength, and repetition rate. The krypton fluoride laser technology is projected, based on experiments, to meet the requirements for wall plug efficiency and durability. The projected wall plug efficiency based on experiments is greater than 7 percent. The Electra laser using laser triggered gas switches has conducted continuous operation for 90,000 shots at 2.5 Hertz operation (ten hours). The Electra laser has achieved greater than 700 Joules per pulse at 1 and 2.5 Hertz repetition rate. The comparison of krypton fluoride laser performance with krypton fluoride kinetics code shows good agreement for pulse shape and laser yield. Development and operation of a durable pulse power system with solid state switches has achieved a continuous run of 11 million pulses into a resistive load at 10 Hz.

Keywords: KrF laser, inertial fusion energy, electron beam, pulsed power, repetitively pulsed

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1. Introduction

A laser driver for direct drive inertial fusion energy (IFE) should have properties including a total overall efficiency of >7% with precise control (~10 picoseconds) of pulse shape, spatially uniform illumination of the target (to minimize hydrodynamic instabilities), an ultraviolet wavelength (to maximize coupling to the target and minimize laser plasma instabilities), and made of rep-rate modular laser systems capable of delivering tens to hundreds of kilojoules per shot throughout a couple years of service. An electron beam pumped krypton fluoride (KrF) laser is a viable approach of reaching all the criteria for a laser fusion energy driver.

The KrF laser is a gas laser. Gas lasers have high volume, are conceptually simple, and its almost impossible to damage the gain medium since heat can be removed quickly from the cavity. The requirements to make a KrF laser are krypton gas, fluorine gas and a pump source. The pump source energizes the gas to form KrF molecules. These KrF molecules are formed in an excited electronic state which dissociates to a repulsive ground state with emission at 248 nm. Molecules with this type of radiation are called excimers. Excimer lasers are commonly used in applications of high reliability and spatial control such as delicate eye surgeries known as LASIK [1] and lithography of microelectronics [2]. The pump source in these applications is a discharge. To obtain larger energies needed for a fusion energy driver electron beams are employed. Electron beam technology allows efficient uniform excitation and ionization of large volumes of laser gas that is scalable to larger systems.

The Nike Laser [3] provides up to 3 kJ of laser light per shot for on demand experimental research in KrF laser-target interactions at the United States Naval Research Laboratory (NRL). Nike routinely (up to 20 shots in eight hours) demonstrates efficient laser amplifier extraction (angularly multiplexing), uniform focal spatial profile utilizing induced spatial incoherence (ISI) [4], and pulse shape control. The largest amplifier of the Nike laser system has been discussed in detail elsewhere [5]. Nike is pumped with two counter streaming electron beams. Each is 60 cm high × 200 cm wide, has a voltage of 640 keV, a current of 540 kA, and a pulse with a flat top portion of 250 ns. The beams deposit their energy into a volume of 60 cm × 60 cm × 200 cm containing krypton, argon and fluorine gas. The electron beams in this reliable operating amplifier are within a factor of two of the power plant size diode for KrF lasers [6] and allows investigation on the relevant physics for optimizing efficiency.

NRL also has the Electra Laser, a repetitively pulsed electron beam pumped 700 Joule KrF laser facility [7]. The Electra main amplifier (shown in Fig. 1) has been described previously [8]. Briefly, two separate pulse power systems provide counter-propagating electron beams, each 500 keV, 100 kA and a flat top pulse width of 100 ns over an area of 30 × 100 cm^2. A stainless steel foil provides a barrier between the vacuum diode and laser gas mix

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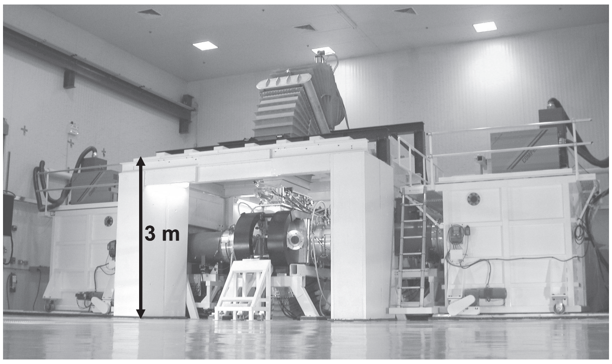

Fig. 1 The rep-rate Electra main amplifier in 700 J oscillator configuration.

containing argon, krypton and fluorine. The Electra main amplifier has been utilized in a six beam angularly multiplexed laser system for 10 shot bursts at 5 Hz [9]. NRL's objective [10] with Electra is to develop technologies to meet the IFE requirements for repetition rate, efficiency, durability and cost. The technologies developed in Electra should be directly scalable to a power plant beam line.

2. Efficiency

Efficiency is an important consideration when evaluating laser fusion energy drivers. The Sombrero power plant study suggested a KrF laser based system could meet the requirement for economical viability [11]. Since the Sombrero study, target designs have steadily improved with new exciting advances such as shock ignition that predict gains of 200 utilizing less than 1 MJ of KrF laser energy [12]. These larger gains would only enhance the economic viability of a KrF laser approach. The wall plug efficiency for a fusion KrF driver is the amount of energy in the laser impinging the target divided by the amount of electrical energy consumed by the laser (including thermal management) for one shot. It is predicted to be approximately ~7% [10]. The overall wall plug efficiency is comprised of five parts; pulse power, hibachi, KrF intrinsic, optics to target, and ancillaries.

The pulsed power efficiency component is the amount of energy in the flat top electron beam divided by the wall plug energy. This definition was chosen for two reasons. First, when scaling to larger systems with longer pulses (400 ns) the flat top section will be a larger percentage of the beam. Secondly, the rise and fall of the voltage pulse will not contribute to laser pumping. Relatively little energy will transmit through the pressure foil and hibachi structure, and the portion that does will not uniformly deposit its energy into the laser gas. Note also that a fast rise and fall voltage pulse reduces the heat load in the pressure foil. The goal of over 80% pulse power efficiency has been demonstrated at NRL using an all solid state pulse power system [13].

The hibachi portion of the overall efficiency is the transport of the flat top portion of the electron beam from the cathode into the laser gas mix. The pressure foil separates the laser gas, which is typically above 1 atmosphere from the vacuum diode. The support structure holding the foil is known as the hibachi. The hibachi provides adequate support to the foil and can provide additional cooling through long channels (ribs) of the hibachi. The Electra laser facility primarily uses a 25 micron thick stainless steel foil as the pressure foil and hibachi which is cooled by water with a rib separation of 44 mm. In using a strip cathode 75% efficiency has been achieved in the Electra experiments at 500 keV [14]. At higher voltages of 800 keV a smaller portion of the electrons would be stopped by the pressure foil, so the efficiency is projected to be greater than 80%. Another aspect of efficiency for large area electron beams is removal or mitigation of the 'transit time instability' [15, 16]. Transit time instability introduces a temporal and spatial non-uniformity that can lead to a reduction in energy deposition in the gas for electron beam pumped lasers and also create a spatially non-uniform gain medium in the laser amplifier. The transit time instability can be mitigated by not allowing the instability to grow by forming the cathode surface with slots or a grid [15, 16]. The cathode made of strips has the additional benefit of avoiding the hibachi rib structure to maximize efficiency.

The least efficient portion of the KrF laser is the transfer of energetic electrons to laser photons. This portion is called intrinsic efficiency, the amount of laser energy output divided by the energy deposited in the gas. Intrinsic efficiencies of 12% are projected based on Electra measurements [7, 10, 17]. These measurements made in oscillator mode were evaluated using Rigrod analysis to find the effect of window transmissivity and operation in oscillator mode to the laser output and efficiency in amplifier mode [17]. The experiments on Electra are consistent with the previously published results of 12-14% intrinsic amplifier power efficiencies [18–20]. Electra measurements have shown the maximum intrinsic efficiency can be attained over a range of laser composition including additions of Helium, which increases the thermal conductivity of the laser gas [20]. High efficiency can be maintained as demonstrated by the rep-rate runs at various frequencies of 700 J per shot (Fig. 2).

The next component of the overall wall plug efficiency is the optics to target. The optics to target account for all of the optical loses after the final electron beam pumped amplifier. Our projection of 95% efficiency is due to the fact that only one transmissive optic (window into target chamber) is necessary after passing the final amplifier window. The angularly multiplexed laser beams can be used with all reflective components to minimize potential losses. The laser beam intensity is low until reaching the reaction chamber. This allows propagation in inert atmospheres without suffering any losses. We estimate seven reflective optics after the amplifier window. The pro-

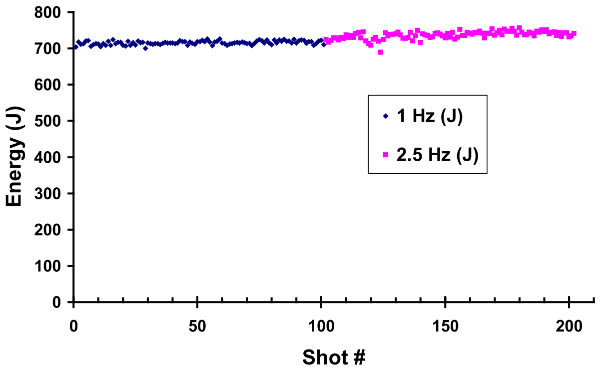

Fig. 2 Reproducible 700 J output of the Electra laser at rep-rates of 1 Hz and 2.5 Hz.

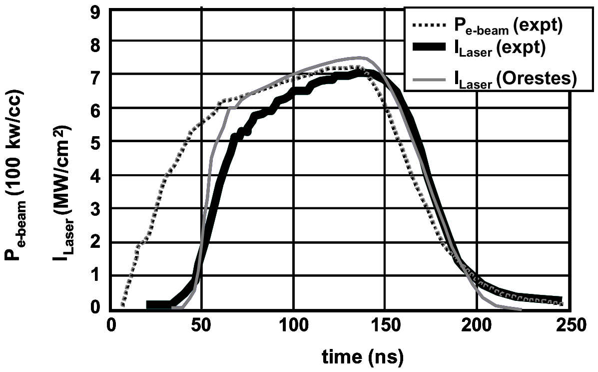

Fig. 3 Comparison of the NRL kinetics code (Orestes) and the Electra oscillator output. Electra experiments have shown increased output to 751 J to even attain better agreement.

jected 95% efficiency is based on 99.5% reflectivity for these eight optics, plus 99% transmission efficiency for the window into the target chamber. The high transport efficiency should be achievable as the intensity and energy flux is low, 0.6 GW/cm^2, and 2.2 J/cm^2. The KrF power plant beam line, 248 nm and ISI beam smoothing, does not require harmonic generation crystals or phase plates. This coupled with the ability of KrF lasers to change the laser spot size on the imploding target in real time, called zooming, and maximizes the useful laser photons reaching the target in a correct manner.

The last part of the overall efficiency is ancillaries. Ancillaries include energy for cooling water pumps for the hibachi and the energy required to supply the required magnetic field in the vacuum diode. Superconducting magnets would be required to keep power requirements low. In addition the motor which powers the recirculator as well as any additional devices for cooling the foil are part of the ancillaries. The excess energy in the gas medium not extracted by the KrF laser goes into heat. This heat could be retrieved and produce additional energy if necessary [21]. The potential amount of heat available can be on the order of 33% of the total wall plug efficiency [21].

3. KrF Kinetics Scaling

A first principles KrF kinetics code, ‘Orestes’, has been developed at NRL to analyse the data from NRL electron beam amplifiers as well as several other laser systems from around the world. Orestes includes the ionization and excitation arising from electron beam deposition [22, 23], plasma chemistry for 24 species subject to 146 reactions, laser transport and time dependent amplified spontaneous emission (ASE) with gain narrowing in three dimensions [24]. Comparisons have been made with Electra in oscillator configuration mode. Figure 3 shows a comparison of a single electron beam shot with the input power deposition of the electron beam and response of the laser intensity measured by photodiodes as well modelling by the code. The pulse shape is very similar and the intensity (yield) is higher in the calculation. Since this measurements new measurements were conducted, which produced high laser yields of 751 J to get even closer agreement. The Orestes code has been developed over a wide range of compositions and pressures [25]. In addition, KrF modelling of the pulse shape for high gain targets has been shown to maintain high efficiencies [26] for large angularly multiplexed laser systems.

4. Durability

Driver durability is a key to attractive economics. A reasonable entry point is to operate without failure for two years at 5 Hz (300 million pulses). The Electra KrF laser has attained 10 hour continuous operation at 2.5 Hz (90,000 shots). Long runs at 5 Hz have been obtained as well. The laser output intensity varies 10% over a 100 minute continuous operation at 5 Hz (Fig. 4). The shot to shot variability is much smaller. Figure 4 shows a typical laser run where initially (first 10,000) the laser yield increases. The initial increase is a slight permanent burn-up of fluorine which reduces absorption in the laser gas as well as fluorinating the interior surface of the windows and reducing the Fresnel reflection a small bit. Subsequently after reaching a maximum the laser yield gradually decreases. Any change observed to the laser gas has been small up to 90,000 continuous shots and the change in laser intensity has been dominated by windows. The interior surfaces of the amplifier windows demonstrate lower transmission to 248 nm after the completion of long laser runs. There is evidence of fluorine etching of the fused silica windows. In the case of Electra, the front window has a change in window transmission from 93% to as low as 65%. The damage was not uniform, and in fact suggests it follows a flow pattern, possibly of the laser gas. In contrast the rear window shows nearly no change even after long runs. We are addressing this problem from a number of angles, including the possibility that flow stagnation may be a contributing factor. Alternatively, we can change the

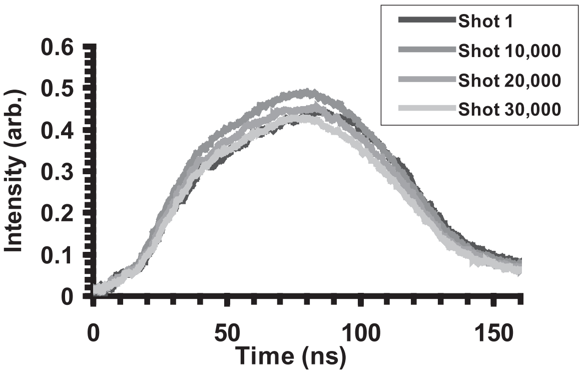

Fig. 4 Rep-rate laser module shows a ~10% intensity variation over 30,000 shots at 5 Hz.

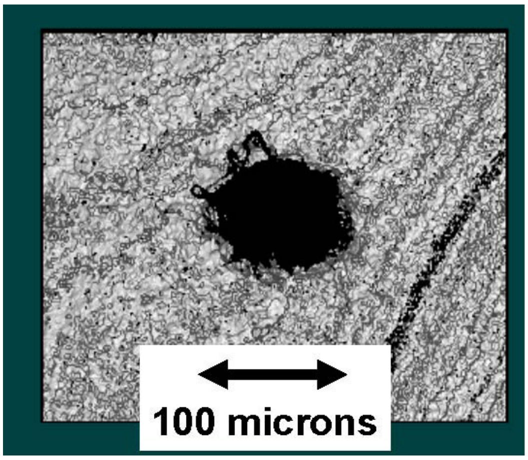

Fig. 5 Pinhole in 25 micron thick stainless steel foil after continuous run at rep-rate in the Electra main amplifier. Detection was achieved by measuring a trace amount of argon utilizing a penning ionization gauge.

window material to either sapphire or magnesium fluoride (MgF_2), which are far more resistant to fluorine etching. In fact, MgF_2 is routinely used in commercial discharge driven KrF systems. Lifetimes in excess of a billion pulses before service has been achieved at comparable intensities and fluorine conditions with discharge lasers [27]. The utilization of alternative window materials such as MgF_2 or sapphire will require development of manufacturing capability and not technology. We are working on reducing intensity variations over long KrF laser runs at 5 Hz as well as increasing the duration from multiple hours to multiple days.

The failure that terminates these long runs is due to pinholes in the stainless steel foil (25 micron thick) between the vacuum diode and the 1.36 atmosphere laser gas mixture. The single pinhole (~100 μm dia.), which stops operation, is very small (2×10^{-8}) relative to the area of the entire foil in the diode ($3000\,\mathrm{cm}^2$). These pinholes have been experimentally linked to voltage reversals in the pulsed power system. We are able to stop operation by detecting the pinholes utilizing a penning ionization gauge and detect low levels of argon. Figure 5 shows a 100 micron diameter hole in a stainless steel foil from operation in the Electra electron beam pumped amplifier. This pinhole was the single cause of a pressure increase in the diode, which terminates the run. The voltage reversals not only cause pinholes in the foil occasionally, but also create damage to the cathode. The damage on the cathode follows the pattern of the ribs of the hibachi (support structure for the foil). Even though the amount of energy in the reversals is very small (less than one percent) this is an important factor affecting long durability and ultimate success of KrF lasers. Several advances in reducing these reversals have led to increasingly longer run durations. These include changing the anode cathode gap as well as removing reflections from the pulse power system of Electra. Electra still exhibits a voltage reversal occasionally from a mistimed shot due to poor triggering of the gas switch. This poor triggering is believed to be the present limit in the foil longevity. The solution is to replace our first generation spark gap based pulsed power system with one based on all solid state components. NRL has developed and operated a durable pulse power system with continuous operation run of 11 million pulses into a resistive load at 10 Hz [13]. This is a subscale system used to develop and demonstrate the technologies. The solid state switches utilized in the pulse power system were built with solid state components which are known to last the 300 million pulses [13] requirement for a power plant. The system has very high precision, with the output voltage varying by less than 1%, with no interruption over the 319 hour long period. The next step will be to deploy a full size solid state system on Electra and repeat our laser longevity runs with a high reliability, high precision pulse power system.

Another aspect of durability is maintaining the high laser beam quality required for fusion throughout the amplifier chain and especially at the target position. We have shown a recirculator carrying 9,000 liters of laser gas composed of argon, krypton and fluorine, allows high laser energy extraction every shot. Phase aberrations in the laser beam can develop if the energy from the previous shot is not fully dissipated and cleared out prior to the shot. These phase aberrations, if allowed to get too large, will manifest in scattering the laser light at the target position. This needs to be avoided in order to allow maximum coupling of all available laser energy to the target. Not only phase aberrations from not fully dissipated energy in the gas, but aberrations will be generated where large varying temperature profiles develop. Along the foils of the amplifier varying temperature profiles cooled by turbulent gas flow can develop which can cause aberrations and distort the laser focal profile at the target. Georgia Tech has experimentally fabricated a rib based jet foil cooling technique [28, 29] that has been shown to minimize aberrations and allow high quality laser beams for fusion in large electron beam pumped amplifiers and keep reasonable temperature profiles [30]. In large aperture electron beam systems the effected region by the temperature foils should become a smaller percentage because the temperature profile disruption is a fixed depth into the laser gas amplifier.

5. Conclusions

The U.S. Naval Research Laboratory is developing KrF laser technology to meet requirements of rep-rate, efficiency and durability for a laser fusion energy driver. Overall wall plug efficiency is attainable based on Electra experiments of the pulsed power, hibachi and KrF intrinsic efficiency. This high laser wall plug efficiency with advance target designs should make inertial fusion energy economically viable. The NRL KrF kinetics code is able to predict performance of may laser systems around the world as well as be a predictive tool for larger KrF electron beam pumped systems with high efficiency and correct pulse shape. Progress in durability by detecting small pinholes in the diode foil and mitigating reverse voltages has lead to achievement of KrF laser runs for 10 continuous hours (90,000 shots at 2.5 Hz). Long laser runs have been achieved at 5 Hz with variation in the laser intensity. Voltage reversals occur occasionally with the current spark gap pulsed power system. These are expected to be eliminated with an all solid state system. This system ran for 11,000,000 shots. The individual solid state components have demonstrated the 300 million pulses required for inertial fusion energy power plant. These advances should result in durable electron beam KrF laser modules. An electron beam pumped krypton fluoride (KrF) laser is well on its way in demonstrating that it is viable in reaching all the criteria for a laser fusion energy driver.

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