# Development of electron beam pumped KrF Lasers for fusion energy

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This paper describes the development of electron beam pumped KrF lasers for inertial fusion energy (IFE). KrF lasers are an attractive driver for fusion, on account of their demonstrated very high beam quality, which is essential for reducing imprint in direct drive targets; their short wavelength (248 nm), which mitigates the growth of plasma instabilities; and their modular architecture, which reduces development costs. This paper presents a basic overview of KrF laser technology as well as current research and development in three key areas: electron beam stability and transport; KrF kinetics and laser propagation; and pulsed power. The work will be cast in context of the two KrF lasers at the Naval Research Laboratory, The Nike Laser (5 kJ, single shot), and The Electra Laser (400 – 700 J repetitively pulsed).

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## I. INTRODUCTION

Direct drive with krypton fluoride (KrF) lasers is an attractive approach to inertial fusion energy (IFE): KrF lasers have outstanding beam spatial uniformity, which reduces the seed for hydrodynamic instabilities; they have short wavelength (248 nm) that increases the rocket efficiency and raises the threshold for deleterious laser-plasma instabilities; they have the capability for "zooming", i.e. decreasing the spot size to follow an imploding pellet and thereby increase efficiency; and they have a modular architecture, which reduces development costs. 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 underway. In addition to these laser-target advantages, the Sombrero Power Plant study showed a KrF based system could lead to an economically attractive power plant [3]. In view of these advances, several world-wide programs are underway to develop KrF lasers for fusion energy. These include programs in Japan [4, 5], China [6], Russia [7], and The United Kingdom [8]. There was also a large program in the United States [9]. The paper here concentrates on current research in the US with two lasers at the Naval Research Laboratory: The Electra laser [10] is a 400-700 J repetitively pulsed system that is being used to develop the technologies that meet the fusion requirements for rep-rate, durability, efficiency and cost. The Nike laser [11] is a 3-5 kJ single shot device that is used to study KrF issues with full-scale electron beam diodes. Nike is also used to investigate laser target interactions and benchmark the codes underlying the target designs. Nike generates a beam with the proper pulse shape required for fusion energy, and ablatively accelerates planar targets with 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.

## II. KrF BASICS

KrF is an excimer (Excited Dimer) laser based on a molecular electronic transition to a ground state which immediately dissociates. There are many rotational / vibrational transitions so KrF lasers have a very large bandwidth (1-3 THz). The fundamental wavelength is 248 nm. Small KrF systems (< 1 Joule, pulses of 10 nsec or less) are pumped with discharges and are routinely used for semiconductor manufacturing. Large amplifiers (10 J to-10's of kJ, 20-1000 nsec), such as the components proposed for a fusion driver, are pumped with electron beams. As shown in Fig. 1, the electron beams are injected into opposite sides of the laser cell and perpendicular to the laser axis. The laser cell is filled with a 1-2 atmosphere mix of krypton, fluorine and argon (a buffer gas). From beam stopping considerations the electron beam voltage, $V_{beam}$, ranges between 300 to 750 keV. For large amplifiers, diode considerations set the impedance to about one ohm, so the current will about 300-750 kA. A thin foil isolates the laser gas from the electron beam vacuum diode and is held by a support known as a hibachi. Typically the laser beam is amplified as it propagates through the cell, is reflected from a rear mirror, and further amplified as it propagates back through the cell out through the entrance. (This is not shown in Figure 1 for clarity purposes). In a repetitive system a recirculator cools and quiets the laser gas between shots. An external magnetic field prevents the electron beam from pinching as it is guided into the laser cell. Large, single shot amplifiers have also been built without a magnetic field [4, 5, 8]. In those systems many smaller diodes are arranged cylindrically about the laser cell. However the magnetically guided systems have been proven to be more efficient, and are more compatible with the gas recirculator required for repetitively pulsed operation.

### A. Beam Smoothing

The large bandwidth of KrF results in a short averaging time which produces a very uniform illumination of the target. This is accomplished through ISI, or "induced spatial incoherence [12, 13]": An aperture is illuminated with incoherent broadband laser light and is imaged through the laser system and focused onto the target. See Fig. 2. The Nike laser at NRL has demonstrated this technique and produces a very uniform focal profile: The rms speckle uniformity in each laser beam is on the order of 0.3-1.3% [11]. This very high uniformity reduces the imprinting (or seed) of modulations on a fusion target, and hence mitigates the growth of hydrodynamic instabilities.

### B. Time scale mismatches.

Electron beams require pulse durations of several hundred nsec to produce significant energy. Yet the relaxation time of (KrF)* is only 7 nsec. This "mismatch" is resolved by continually extracting the laser light during the electron beam pulse. Another mismatch occurs because the target physics requires an 8-16 nsec drive pulse. This is solved by "angular multiplexing" the laser beams [14]. A single laser pulse (~ 10 nsec) is divided into a series of pulses that are sequentially injected into the amplifier, with each injected at a different angle. Thus the amplifier "sees" one continuous pulse of duration of 100's nsec. After amplification the delays are removed to allow the 10 nsec beams to simultaneously illuminate the target.

### C. Pulse Shaping and Zooming

For a fusion target, the laser pulse must be "shaped" with a low intensity foot followed by a high intensity main pulse. The foot raises the isentrope of the ablator which lowers its susceptibility to hydrodynamic instabilities [1]. Pulse shaping can be readily achieved in all high power fusion lasers. In KrF laser systems this is accomplished by adding a Pockels cell after the aperture to modulate the light. It is also beneficial to decrease the laser focal spot to match the compressing target. This can boost the laser absorption by as much as 30% (1). "Zooming" is straightforward with a KrF laser. Three parallel tracks are added to the optical layout shown in Fig 2. Each track has its own unique sized aperture and a Pockles cell. By sequentially running the laser beam through smaller and smaller apertures, the laser spot size is decreased. One candidate target design [1] has three zooming steps.

## III. RECENT ADVANCES IN KrF LASER RESEARCH AND DEVELOPMENT

We have developed and built a First Generation Pulsed Power System that produces two 500 keV, 100 kA, 100 nsec electron beams [15]. While the technology used in this system does not meet the IFE efficiency or durability requirements, it does have the required electrical output and repetition rate. Thus it will give a platform for the development of the other laser components while a pulsed power system that can meet the IFE requirements is being developed The First Generation 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. (This is a simple matter 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. Electron beam runs of several thousand shots are commonplace. The first generation laser components have been installed and Electra has been run as a laser oscillator producing up to 400 J of laser light in a single pulse. We have also run Electra as a laser in a burst mode, but the burst durations are limited because the gas recirculator has not yet been installed.

## A. Electron beam propagation and the foil support structure

Large area diodes are subject to the *transit time instability*. This instability was observed with experiments on the Nike 60 cm amplifier and successfully modeled [16] with a particle-in-cell code. The instability imparts an axial velocity spread to the electron beam, which lowers the energy transfer efficiency into the laser gas. The modeling showed the instability is unaffected by the magnetic field strength: It was varied between 1 and 100 kG with no effect. (The nominal field in the experiments is 2 kG.) The modeling also showed that slotting the electron beam cathode and loading the slots with microwave absorbing material can mitigate this instability. The slot width, depth, and pitch are precisely chosen so the phase velocity of the wave associated with the instability is close to zero. This concept has been demonstrated on the Nike laser [17]. As shown in Fig 3, the slots both delay the onset of the instability and lower the energy in the high frequency modes. We believe we can completely eliminate the instability by adding resistors into the slots (to widen the frequency range where the attenuation is important) and/or by slotting the cathode in the other direction.

We have developed a hibachi concept that demonstrates an energy deposition transmission efficiency of up to 75% on Electra (500 keV). The deposition efficiency is defined as the ratio of the power deposited in the laser gas divided by the electrical power in the diode during the “flat top” portion of the electrical power pulse. The high transmission 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 conceptually simple, these are difficult in practice: The beam strips spread due to the highly non-uniform electric fields caused by elimination of the anode, and they rotate and shear due to the applied magnetic field. We compensate for these by narrowing the emitters and “counter-rotating” them so the beam strips propagate parallel to the ribs when they enter the hibachi. This is shown in Figure 4. The strips are consistent with eliminating the transit time instability as described above. While the topology of the strips can be determined empirically, this does not give us the predictive capability needed to design larger systems. This is a rather complex phenomenon to model and requires a full 3-D PIC simulation of the exact experimental geometry, including the rib structure, laser gas, and magnetic field. This was achieved with the Large Scale Plasma (LSP) code [18]. The simulations accurately predict both the cathode counter rotation angle and the energy deposition efficiency [19]. A simulation of a beam “strip” is also shown in Figure 4.

## B. KrF Physics development

We have developed the "Orestes" KrF Physics code to both predict the behavior of Electra and as a tool to design full scale (30-100 kJ) systems. Orestes combines the relevant physics into a single KrF Physics code. The e-beam ionization and excitation is determined from a Boltzmann analysis of the electron energy distribution function [20, 21]. The code includes spatial resolution along the laser axis to account for the change in gain from mirror to front window. The code carries out detailed energy conservation (better than 1%) to account for the e-beam input, laser input, plasma thermal and internal energies, as well as the Amplified Spontaneous Emission (ASE), and laser output. Besides the gas phase kinetics, Orestes includes two electronic states of KrF with vibrational levels up to ν=53, and includes transitions between these states and levels. The code includes laser propagation along the characteristic axis, and ASE transport in 3-D. The time dependence is fine enough to allow modeling short pulses (shorter than the transit time between the amplifier sides). ASE gain narrowing is included by performing a multi-frequency transport of the incoherent light around 248 nm. Orestes has been benchmarked against a wide range of KrF experiments under different conditions. Using experimental energy depositions, Orestes predicts the optimal output for Electra, as an amplifier, to be between 550 J and 850 J, depending on the experimental conditions.

## C. Advanced Pulsed Power

We designed a pulsed power system that can meet IFE requirements for rep-rate (5 Hz), durability (> 3 x $10^8$ shots), efficiency (85%), and cost ($8.50/pulsed power Joule). The system is based on an all-new, four-layer, solid-state switch that is optically triggered by two on-board diode laser arrays. The lasers flood the entire switch volume with photons to yield switching times of less than 100 nsec. The lasers are kept on during the entire electrical current pulse to maximize efficiency. We call this device a *Laser Gated and Pumped Thyristor*, *or LGPT* [22]. For the first tests, we modified an off-the-shelf Thyristor to accommodate a single diode laser array and its optical coupling. The switch operated at 3.2 kV for $10^5$ shots at 5 Hz. The current density was 2.7 kA/cm$^2$ (121% of the IFE requirement) and current rate of rise of was 1.4 x $10^{10}$ A/sec/cm$^2$ (154% of the IFE requirement). We have built a second-generation switch using advanced, purpose-built construction techniques. It has operated at 15.2 kV and held 24 kV in a pulse charge. A version of this advanced switch, that employs both anode and cathode gating arrays, is being assembled now. This switch has a wide range of other applications.

## IV. PROJECTED OVERALL EFFICIENCY OF KrF.

Based on our present understanding, we expect the overall efficiency of a large KrF system, from "wall plug" to target, to be about 7%. The breakdown is based on 85% for the pulsed power (wall plug to flat top electron beam), 80% for the hibachi transmission (using a 750 keV electron beam vs. the 500 keV used on Electra), an intrinsic KrF efficiency of 12% [23, 24], a loss of 5% for the auxiliary components (cooling supplies, etc.) and a 5% loss through the optical train.

## V. ACKNOWLEDGEMENTS

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IV. REFERENCES

[1] S.E. Bodner, D.G. Colombant, A.J. Schmitt and M. Klapisch, Phys of Plasma*s* **7,** 2298, (2000).

[2] D. Colombant, S.E. Bodner, A. J. Schmitt, *et al.,* Phys. Plasmas **7,** 2046, (2000).

[3] I.V. Sviatoslavsky, M.E. Sawan, R.R. Peterson, G.L. Kulcinski, J.J. MacFarlane, L.J. Wittenberg, H.Y. Khater, E. A. Mogahed and S.C. Rutledge*,* Fusion Technology, **21**, 1470, (1992).

[4] I. Okuda, E. Takahashi, I. Matsushima, Y. Matsumoto, H. Yashiro, E. Miura, T. Tomie, and Y. Owandano, Fusion Engineering and Design, **44,** 377 (1999).

[5] I. Okuda, J. Ma, E. Takahashi, I. Matsushima, Y. Matsumoto, S. Kato, and Y. Owandano, Appl Physics B- Lasers and Optics, **75**, 623 (2001).

[6] N. Wang. Y. Shan, W. Ma, *et al.,* Lasers and Particle Beams, **20**, 119 (2002).

[7] V.D. Zvorykin, S.V. Arlantsev, V.G. Bakaev, O.V. Rantsev, P.B. Sergeev, G.V. Sychugov and A.Yu. Tserkovnikov. Laser and Particle Beams, **19,** 609, (2001).

[8] E. Divall, C. Edwards, G. Hirst, *et al.,* Journal Modern Optics, **43**, 1025 (1996).

[9] L. Roscha, F. Riepe, J. Hanlon, J. NcLeod, M. Kang, B. Kortegaard, M. Burrows, P. Bowling, Fusion Technology, **11**, 497, (1987).

[10] J.D. Sethian, M. Friedman, J. Giuliani, R. Lehmberg, M. Myers, S. Obenschain, F. Hegeler, S. Swanekamp, in Inertial Fusion Sciences and Applications, edited by K.A. Tanaka, D.D. Meyerhoffer and J. Meyer-ter-Vehn, Elsevier, NY, 495 (2002).

[11] S.P. Obenschain, S.E. Bodner, D. Colombant, *et al.*, Phys of Plasmas, **3**, 2098, (1996).

[12] R.H. Lehmberg and J. Goldhar, Fusion Tech. **11,** 532, (1987)

[13] R.H. Lehmberg, A.J. Schmitt and S.E. Bodner, J. Appl. Physics, **68,** 2680, (1987).

[14] J.A. Hanlon and J. McLeod, Fusion Tech. **11**, 634, (1987).

[15] J.D. Sethian, M. Myers, I.D. Smith, *et al.*, IEEE Trans Plasma Sci, 28, 1333 (2000)

[16] M. Friedman, S. Swanekamp, S. Obenschain, Y. Chan, L. Ludeking and D. Smithe, Appl. Phys. Lett. **77,** 1053, (2000).

[17] M. Friedman, M. Myers, S.B. Swanekamp, Y. Chan, J.D. Sethian and S. Obenschain, al Appl. Phys. Lett. **81,** 1597, (2002).

[18] LSP is a software product of Mission Research Corporation, Albuquerque, NM 87110; http://www.mrcabq.com.

[19] D. V. Rose, D. R. Welch, F. Hegeler, S. B. Swanekamp, M. C. Myers, and J. D. Sethian, submitted to J. Appl. Phys. (2002).

[20] J.L. Giuliani, G. M. Petrov and A. Dasgupta, Phys of Plasmas, **92,** 1200, (2002).

[21] G.M. Petrov, J.L. Giuliani and A. Dasgupta, Phys of Plasmas, **91,** 2662, (2002).

[22] D. Weidenheimer, Proceedings, Power Modulator Conference, Hollywood, CA, June 31-July 2, 2002.

[23] A.E. Mandl, D.E. Klimek, and E.T Salesky, et al, Fusion Technology **11,** 542, (1987).

[24] A. Suda, M. Obara, and A. Noguchi, Appl. Phys. Lett, **51,** 218, (1987).

## FIGURE CAPTIONS

Figure 1: Components of an electron beam pumped KrF Laser.

Figure 2: Optical train of a KrF laser. The focal profile is rapidly smoothed on the time scales of interest. The profile at the aperture is imaged onto the target. A Pockels cell is used to modulate the laser pulse shape and zoom the laser beam.

Figure 3: Suppression of the transit time instability using a slotted cathode. The left hand graphs show the current density and dI/dt (the rate of change of current). The right hand graphs show the Fast Fourier Transform of the dI/dt signal. Upper row is for a monolithic cathode, lower is for a slotted cathode.

Figure 4: Drawing of hibachi concept (upper), photo of cathode showing the counter-rotated emitter strips (middle), and LSP modeling of beam propagation past ribs (lower).

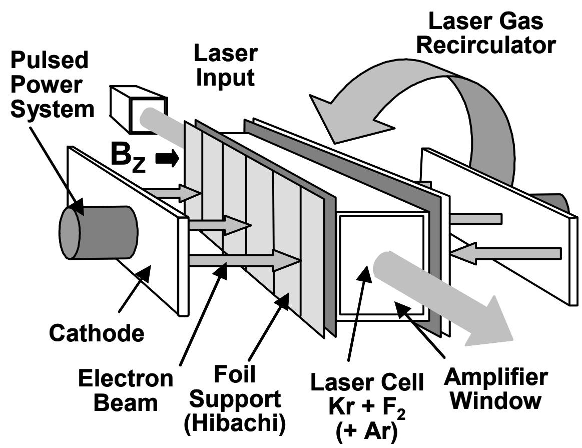
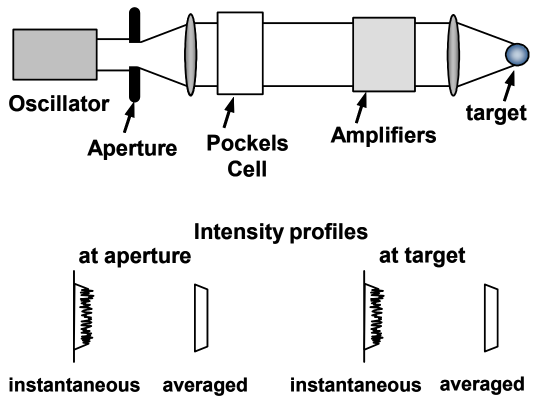

Laser Gas
Recirculator
Pulsed
Power
System
Laser
Input
$B_Z$
Cathode
Electron
Beam
Foil
Support
(Hibachi)
Laser Cell
$Kr + F_2$
(+ Ar)
Amplifier
Window

Figure 1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Aperture
Pockels Cell
Amplifiers
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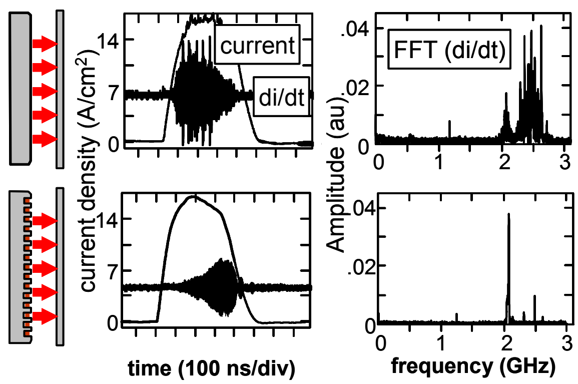
instantaneous
averaged

Figure 2



14
7
0
current
di/dt
current density (A/cm2)
14
7
0
time (100 ns/div)
.04
.02
0
FFT (di/dt)
0
1
2
3
Amplitude (au)
.04
.02
0
0
1
2
3
frequency (GHz)


Figure 3

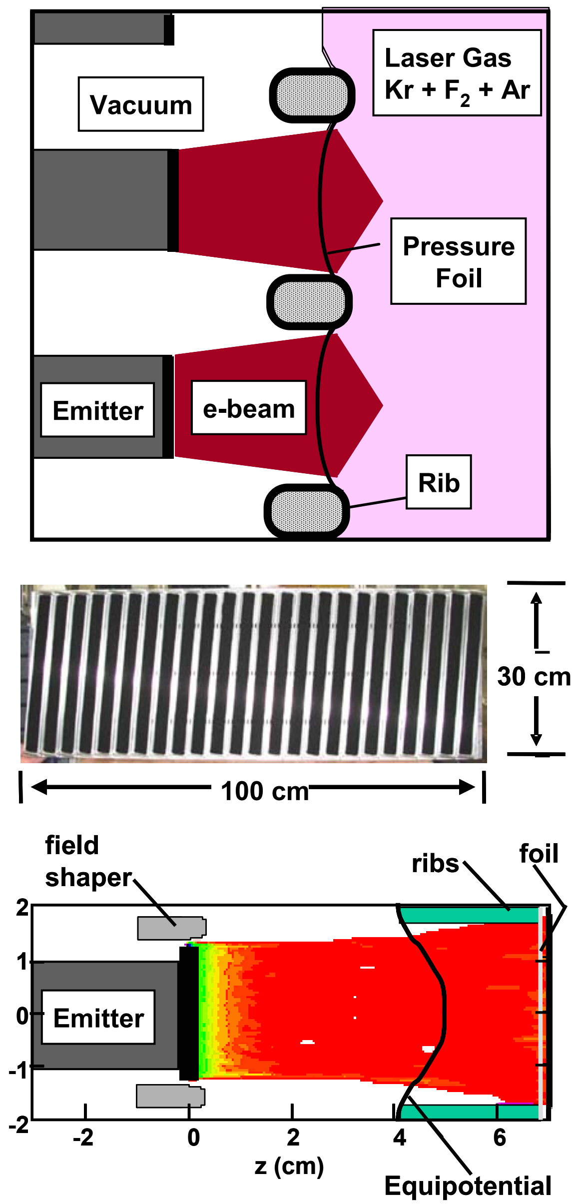

Laser Gas
Kr + F2 + Ar
Vacuum
Pressure
Foil
Emitter
e-beam
Rib
30 cm
100 cm
field
shaper
ribs
foil
2
1
0
-1
-2
Emitter
-2
0
2
4
6
z (cm)
Equipotential

Figure 4.