

Electra: Repetitively Pulsed 700 J, 100 ns Electron Beam Pumped KrF Laser

F. Hegeler¹, J.D. Sethian, M.C. Myers, M.F. Wolford, M. Friedman¹, J.L. Giuliani, P. Burns², and R. Jaynes³

Plasma Physics Division, Naval Research Laboratory, Washington, DC 20375 USA

¹Commonwealth Technology, Inc., Alexandria, VA 22315 USA

²Research Support Instruments, Lanham, MD 20706 USA

³Science Applications International Corporation, McLean, VA 22102 USA

Abstract—This paper presents a brief overview of the Electra laser system and report on the most recent results. The laser system consists of an electron beam pumped main amplifier with an aperture of 30x30 cm², an e-beam pumped 10x10 cm² pre-amplifier, and a commercial discharge laser serving as the seed oscillator. The main amplifier, currently operated as an oscillator, has demonstrated single shot and rep-rate laser energies exceeding 700 J, with a pulse width of 100 ns at 248 nm. Continuous operation of this laser in an oscillator mode has lasted for more than 2.5 hours without failure at 1 and 2.5 Hz. Tests at higher repetition rates and longer runs are ongoing. The pre-amplifier uses a fast gas Marx, pulse forming lines, a single stage magnetic switch, and transit time isolators and operates with a rep-rate of up to 5 Hz.

I. INTRODUCTION

Electra is a repetitively pulsed, electron beam pumped Krypton Fluoride (KrF) laser at the Naval Research Laboratory that is developing the technologies that can meet the Inertial Fusion Energy (IFE) requirements for durability, efficiency, and cost. The technologies developed on Electra should be directly scalable to a full size fusion power plant beam line [1-4]. The Electra laser system has two electron beam pumped systems: (a) the main amplifier and (b) the pre-amplifier. Both systems have been developed independently, and they will be integrated into one laser system. Until this time, the main amplifier is operated as an oscillator [5].

II. ELECTRA KrF LASER PROGRAM

The key components under development are a durable electron emitter, a long-lived, pressure foil structure (hibachi); a laser gas recirculator, and long lived optical windows (see Fig. 1). There is also an ongoing program in the physics of KrF lasers [6]. All of these components affect the efficiency and durability of the overall laser. In addition, the durability of some laser components are interlinked, e.g., the durability of the pressure foil is, in part, dependent on the performance of the pulsed power system and the cathode. The following subsections will discuss some of the KrF laser components in more detail.

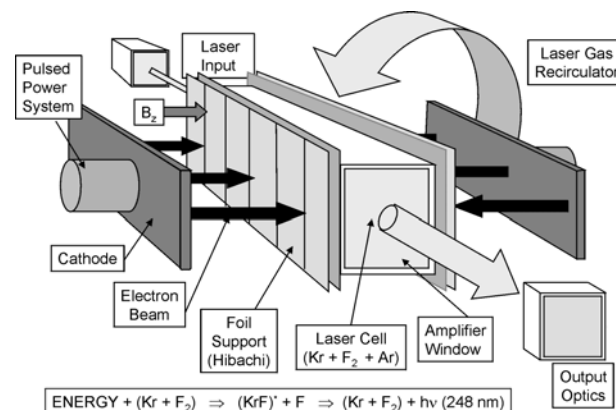


Fig. 1. The main components of an electron beam pumped KrF laser.

A. Pulsed Power Systems

Each of the two pulsed power systems of the main amplifier consists of a capacitor bank that feeds the primary side of a 1:12 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 output switches. The system operates at 400-550 kV, 70-120 kA, 140 ns FWHM pulse duration, and rep-rates of up to 5 Hz [7]. Erosion of the output switch electrodes requires a refurbishment every 50,000 to 100,000 shots. This first generation system serves as a test bed to develop the KrF laser components on the main amplifier, while the next generation pulsed power system is developed on the pre-amplifier.

Spark gap switches need to be eliminated to improve the durability and efficiency of the pulsed power system. The 175 kV, 70 kA pre-amplifier uses a fast 10-stage Marx, pulse forming lines, a magnetic switch, and transit time isolators. Currently, the Marx uses spark gaps with electrode lifetimes of 100,000 shots. The system operates at rep-rates of up to 5 Hz and with a jitter of less than 900 ps. In 2008, the spark gaps will be replaced with laser gated and pumped thyristors that are under development by L3 Communications [8].

B. Cathodes and Electron Beams

The cathode in the main amplifier requires a fast risetime (< 40 ns), uniform current emission without hot spots, low plasma generation in the A-K gap to prevent diode impedance

Work supported by U.S. Department of Energy, NNSA/DP

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 01 MAY 2006		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE Electra: Repetitively Pulsed 700 J, 100 ns Electron Beam Pumped KrF Laser				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Plasma Physics Division, Naval Research Laboratory, Washington, DC 20375 USA				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES See also ADM001963. IEEE International Power Modulator Symposium (27th) and High-Voltage Workshop Held in Washington, DC on May 14-18, 2006, The original document contains color images.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 4	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

collapse, and a current density of 30-50 A/cm² at a rep-rate of 5 Hz. Moreover, the cathode system needs to be simple, durable, and efficient. Initial experiments were performed with a low-cost double density velvet cloth to develop a cathode configuration for efficient electron beam transport through the hibachi into the laser gas (see Fig. 2). With a counter-rotated strip cathode, about 70% of the flat top diode electron energy has been deposited in the laser gas of the main amplifier at 500 kV using a hibachi configuration with a 25 μ m thick stainless steel foil [9]. We expect an electron energy deposition efficiency of 80% at a diode voltage of 800 kV used in a full energy beam line.

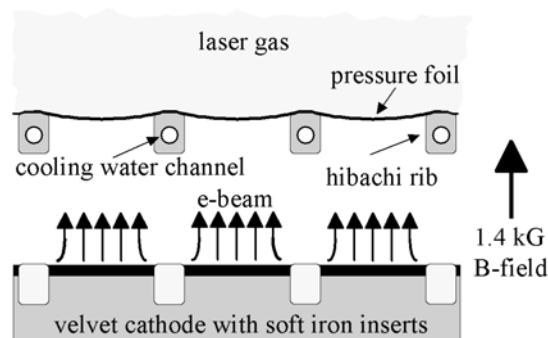


Fig. 2. Strip cathode allows efficient electron beam transport into the laser gas.

With the velvet cathode, the laser durability was limited to a few 100's of continuous shots at rep rates of 1 to 5 Hz before a hole developed in the stainless steel foil. Examination of the cathode showed "burned" spots of the velvet cloth that most likely produced highly non-uniform electron emission (i.e., hot spots). The durability of the velvet cathode was significantly improved with a 5 cm thick cordierite ceramic honeycomb that was placed 2 mm above the velvet cloth [10-11]. The ceramic honeycomb/velvet cathode showed sufficient robustness to allow continuous operation of up to 10,000 shots at 1 and 2.5 Hz.

To further enhance the durability of the ceramic honeycomb cathode, the velvet cloth was replaced with a carbon fiber cathode made by Energy Science Laboratories, Inc. [12]. With the ceramic honeycomb/carbon fiber cathode, the laser durability increased to more than 24,900 continuous shots at 2.5 Hz. Future improvements will include cathode cooling and modifications of the ceramic honeycomb construction. More robust ceramic materials, such as silicon carbide and alumina are also under investigation.

C. Pressure Foil Cooling

The pressure foil separates the atmospheric laser gas from the vacuum diode. This metal foil should be low in both density and thickness to reduce absorption of the electron beam energy. For enhanced durability, the pressure foil requires high mechanical strength, ductility, and resistance to fluorine. The electron beam deposits some fraction of its energy in the foil resulting in an increase in foil temperature, while the mechanical strength of the foil is reduced at higher

temperatures. Therefore, cooling is essential to keep the foil below its long-term fatigue stress.

The foil temperature can be limited by convective, conductive, and radiative cooling. Forced convective cooling uses the recirculating laser gas and is enhanced by turbulent gas flow at the foil. Conduction cooling removes the heat of the foil by the water-cooled hibachi ribs and requires foil with a high thermal conductivity. Cooling by radiation alone requires high temperatures, where the mechanical strength of the foil is inadequate for our purposes.

The forced convection cooling of the foil was improved by adding 10% of helium to the laser gas with negligible reduction of the laser energy output. The foil temperature, measured with an infrared pyrometer, was kept below 250°C for the 25 μ m thick stainless steel foil. The temperature measurements were performed during an actual main amplifier laser run at a rep-rate of 2.5 Hz, with strip velvet cathodes (see Fig. 3). Cooling by radiation is minimal at these foil temperatures, and cooling by thermal conduction is negligible due to the low thermal conductivity of stainless steel. It is expected that the foil temperature will be below 500°C for strip cathodes operating at 5 Hz.

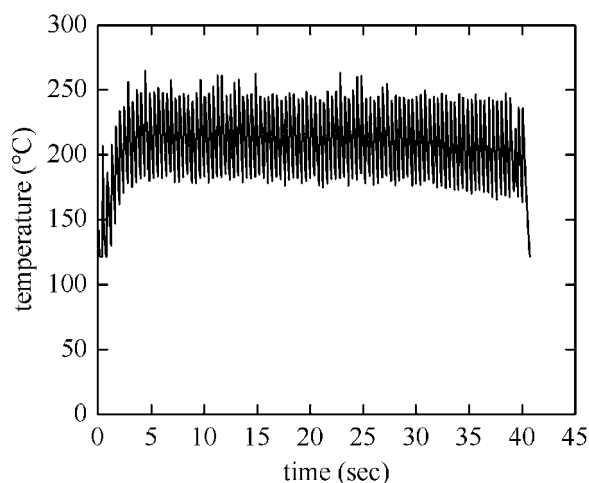


Fig. 3. Temperature of a 25 μ m thick stainless steel foil using a strip cathode at 2.5 Hz for 101 shots.

D. Laser operation

The main amplifier of Electra is operated as an oscillator by using a rectangular flat mirror (32x36 cm²) with a 98.5% reflectance coating at 248 nm and a parallel, uncoated fused silica output coupler (33x35 cm²) that provides a reflection of 8% (total of both surfaces). Two single-sided 248 nm AR coated windows, tilted at 14 degrees, enclose the laser cell with their uncoated surfaces exposed to the laser gas.

Figs. 4 and 5 show that the laser output power of the main amplifier is highly reproducible during rep-rated operation. These experiments used a laser gas composition of 39.7% Kr, 60% Ar and 0.3% F₂, at a total pressure of 1.36 atm, and with 25 μ m thick stainless steel pressure foils. The oscillator produced average output energies of 700 J for 400 continuous shots with strip cathodes (see Fig. 4). These cathodes maximize the electron beam power deposition in the laser gas,

as shown in Fig. 2. With the monolithic ceramic cathode, the hibachi ribs intercept a large fraction of the electron energy, which leads to lower electron power depositions in the laser gas (see Fig. 5). Although the laser energy is reduced to 300 J per shot with the monolithic ceramic cathode, the overall laser durability is significantly increased to more than 10,000 continuous shots. The ceramic cathode will be patterned into strips after cathode improvements as described in section II.B. are completed.

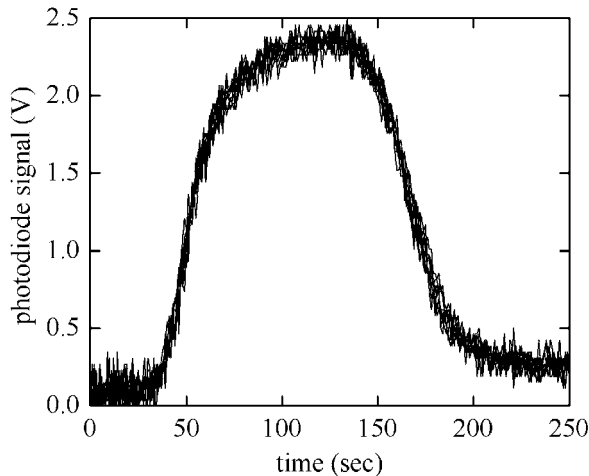


Fig. 4. Laser power profile for 400 continuous shots at 1 Hz, with a laser output energy of 700 J. The graph shows the first and every 50th waveform.

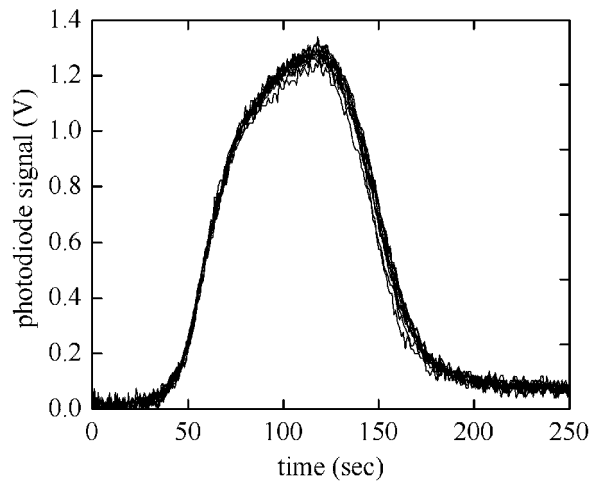


Fig. 5. Laser power profile for 10,000 continuous shots at 1 Hz, with a laser output energy of 300 J. The graph shows the first and every 1,000th waveform.

A commercial KrF discharge laser has been used to seed the pre-amplifier and output energies of 23 J have been achieved in single shot mode. The pre-amplifier input energy was 0.5 J. For these initial experiments, the pre-amplifier with a laser aperture of $10 \times 10 \text{ cm}^2$ used monolithic velvet cathodes and a simple inefficient aluminum hibachi. No attempt was made to pattern the electron beam resulting in a low efficiency system. Laser gas mixture was 19.7% Kr, 80% Ar and 0.3% F_2 at a total pressure of 1.09 atm. Each of the two diodes of the pre-

amplifier operated at 175 kV, 70 kA, and a FWHM of 60 ns. Output laser energies of up to 40 J are expected with a more efficient next generation hibachi and strip cathodes.

III. SUMMARY

The Electra laser program has been successful in advancing the technologies required for a durable and efficient KrF laser. Current achievements include high electron beam deposition efficiency into the laser gas, successful hibachi foil cooling using forced convection that will maintain the foil below stress limits at 5 Hz, and an advancement in durability of the overall laser system by attaining 24,900 continuous shots at 2.5 Hz. Future work will include the continuing development of the durable, high performance ceramic cathode. It is anticipated that within next 18 months the main amplifier will exceed 20,000 continuous shots at 5 Hz.

IV. ACKNOWLEDGEMENTS

The authors are grateful to T. Albert, J. Dubinger, K. Gunlicks, R. Jones, A. Mangassarian, K. Oakley, J. Parish, and W. Webster for the technical support of the experiments.

V. REFERENCES

- [1] J.D. Sethian, M.C. Myers, J.L. Giuliani, R.H. Lehmberg, P.C. Kepple, S.P. Obenschain, F. Hegeler, M. Friedman, M.F. Wolford, R.V. Smilgys, S.B. Swanekamp, D. Weidenheimer, D. Giorgi, D.R. Welch, D.V. Rose, and S. Searles, "Electron beam pumped krypton fluoride lasers for fusion energy," *Proc. IEEE*, vol. 92, pp. 1043-1056, July 2004.
- [2] M.C. Myers, J.D. Sethian, J.L. Giuliani, R. Lehmberg, P. Kepple, M.F. Wolford, F. Hegeler, M. Friedman, T.C. Jones, S.B. Swanekamp, D. Weidenheimer, and D.V. Rose, "Repetitively pulsed, high energy KrF lasers for inertial fusion energy," *Nucl. Fusion*, vol. 44, pp. S247-S253, November 2004.
- [3] J.D. Sethian, M. Friedman, R.H. Lehmberg, M. Myers, S.P. Obenschain, J. Giuliani, P. Kepple, A.J. Schmitt, D. Colombant, J. Gardner, F. Hegeler, M. Wolford, S.B. Swanekamp, D. Weidenheimer, D. Welch, D. Rose, S. Payne, C. Bibeau, A. Baraymian, R. Beach, K. Schaffers, B. Freitas, K. Skulina, W. Meier, J. Latkowski, L.J. Perkins, D. Goodin, R. Petzoldt, E. Stephens, F. Najmabadi, M. Tillack, R. Raffray, Z. Dragojlovic, D. Haynes, R. Peterson, G. Kulcinski, J. Hoffer, D. Geller, D. Schroen, J. Streit, C. Olson, T. Tanaka, T. Renk, G. Rochau, L. Snead, N. Ghoneim, and G. Lucas, "Fusion energy with lasers, direct drive targets, and dry wall chambers," *Nucl. Fusion*, vol. 43, pp. 1693-1709, December 2003.
- [4] J.D. Sethian, M. Friedman, J.L. Giuliani, R.H. Lehmberg, S.P. Obenschain, P. Kepple, M. Wolford, F. Hegeler, S.B. Swanekamp, D. Weidenheimer, D. Welch, D.V. Rose, and S. Searles, "Electron beam pumped KrF lasers for fusion energy," *Phys. Plasmas*, vol. 10, Part 2, pp. 2142-2146, May 2003.
- [5] M.F. Wolford, F. Hegeler, M.C. Myers, J.L. Giuliani, and J.D. Sethian, "Electra: Repetitively pulsed, 500 J, 100 ns, KrF oscillator," *Appl. Phys. Lett.*, vol. 84, pp. 326-328, January 2004.
- [6] J.L. Giuliani, P. Kepple, R.H. Lehmberg, M.C. Myers, J.D. Sethian, M.F. Wolford, F. Hegeler, and G. Petrov, "Orestes: A kinetics model for electron beam pumped KrF lasers," *3rd International Conference on Inertial Fusion Sciences and Applications*, Monterey, CA, pp. 580-583, September 2003.

- [7] J.D. Sethian, M. Myers, I.D. Smith, V. Carboni, J. Kishi, D. Morton, J. Pearce, B. Bowen, L. Schlitt, O. Barr, and W. Webster, "Pulsed power for a rep-rate, electron beam pumped KrF laser," *IEEE Trans. Plasma Sci.*, vol. 28, pp. 1333-1337, October 2000.
- [8] D.M. Weidenheimer, D. Morton, G. James, D. Knudsen, D. Giorgi, and T. Navapanich, "Scaled-up LGPT (Laser Gated and Pumped Thyristor) devices at KrF IFE (Inertial Fusion Energy) operating parameters," (*this conference*).
- [9] F. Hegeler, D. V. Rose, M. C. Myers, J. D. Sethian, J. L. Giuliani, M. F. Wolford, and M. Friedman, "Efficient electron beam deposition in the gas cell of the Electra laser," *Phys. Plasmas*, vol. 11, pp. 5010-5021, November 2004.
- [10] M. Friedman, M. Myers, F. Hegeler, S.B. Swanekamp, M.F. Wolford, J.D. Sethian, and L. Ludeking, "Emission of an intense large area electron beam from a slab of porous dielectric," *J. Appl. Phys.*, vol. 96, pp. 7714-7722, December 2004.
- [11] M. Friedman, M. Myers, F. Hegeler, S.B. Swanekamp, J.D. Sethian, and L. Ludeking, "Emission of an intense electron beam from a ceramic honeycomb," *Appl. Phys. Lett.*, vol. 82, pp. 179-181, January 2003.
- [12] Further information is provided at: <http://www.esli.com>