THERMAL LOADING OF THIN METAL FOILS USED AS ELECTRON BEAM WINDOWS FOR A KRF LASER *

F. Hegeler[a),b)], J.L. Giuliani, J.D. Sethian, M.C. Myers, M.F. Wolford[c)], and M. Friedman[a)]
Naval Research Laboratory, Plasma Physics Division, Washington, DC 20375

Abstract

This paper presents experimental results of the foil temperature on the rep-rated electron beam pumped KrF laser during 50-shot bursts at 1 Hz and 5 Hz. The experiments demonstrate improved convective cooling of the foil during repetitive operation by confining the recirculating laser gas to flow along the hibachi foils.

I. INTRODUCTION

Electra is a repetitively pulsed, electron beam pumped krypton fluoride (KrF) laser at the Naval Research Laboratory that is developing technologies to meet the Inertial Fusion Energy (IFE) requirements for durability, efficiency, and cost. One of the challenging laser components is the pressure foil that separates the diode vacuum from the atmospheric laser gas. 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 key to very long-term durability lies in keeping the foil cool. That in turn requires a thorough understanding of the heat loads. The heat load depends not only on the foil material and thickness, but also on the laser gas mixture (that influences electron backscattering) and the low energy electrons from the opposite electron beam.

The foil temperature can be limited by convective, conductive, radiative, and/or mist cooling (i.e., foils are convectively cooled by a thin water film that does not undergo a phase change in this application). 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 foils with a high thermal conductivity. Cooling by radiation is most efficient at high temperatures, but the mechanical strength of the foil is significantly reduced at these temperatures. Water mist can keep the foils cool but requires that the e-beam passes through a two foil system as well as the water mist, thus reducing the e-beam energy deposition in the laser gas. This paper concentrates on the experimental investigation of convection cooling (e.g., cooling by conduction and radiation are secondary effects).

II. EXPERIMENTAL SETUP

A description of the Electra KrF laser components is found in references [1-3]. The diode operates at 500 kV, 110 kA, and a FWHM of 140 ns. Fig. 1 shows the configuration of the foil temperature measurements. The pressure foil, which separates the laser gas from the diode vacuum, is supported by a hibachi that is comprised of a series of ribs. They are 13 mm deep, 10 mm wide, 350 mm long, and they have a 44 mm rib-to-rib spacing with 24 rib opening. The center of each rib is cooled by water to remove excess heat from the ribs. The hibachi is not designed for conductive cooling of the pressure foil since the ribs are made out of carpenter steel MP35N that has a low thermal conductivity. Furthermore, the water rate flow is too small to remove sufficient heat. All measurements discussed in this paper use a 25 μm thick stainless steel (SS) pressure foil. A type T thermocouple with 50 μm thick wires, located in the middle of a hibachi rib opening, measures the foil temperature. The foil heat load is generated by an e-beam that propagates from the diode vacuum into the laser gas region and deposits some of its energy in the pressure foil. Two cathode configurations have been used: a monolithic cathode with an area of either 27x97 cm^2 or 35x105 cm^2 (see Fig. 1a), or a strip cathode that contains 24 strips, each with a 23 mm × 263 mm emitter surface area. [4-5] The latter patterns the electron beam to miss the hibachi ribs, and allows more of the e-beam to be deposited into the laser gas.

During repetitive laser operation, the laser gas must be quiescent on each shot to ensure a uniform amplified laser beam. This is accomplished by a 9,000 liter laser gas recirculator. In addition, the recirculating gas is used to cool the pressure foil (see Fig. 2). Louvers are installed in the laser cell to enhance the convective cooling of the foil. Open louvers (see Fig. 2a) provide a more uniform gas flow in the laser cell. Closed lovers (see Fig. 2b) increase

---

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

[a)] Commonwealth Technology, Inc., Alexandria, VA 22315
[b)] email: fhegeler@this.nrl.navy.mil
[c)] Science Applications International Corp., McLean, VA 22102

0-7803-9189-6/05/$20.00 ©2005 IEEE.

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **JUN 2005**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Thermal Loading Of Thin Metal Foils Used As Electron Beam Windows For A 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) **Naval Research Laboratory, Plasma Physics Division, Washington, DC 20375**	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 ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013.

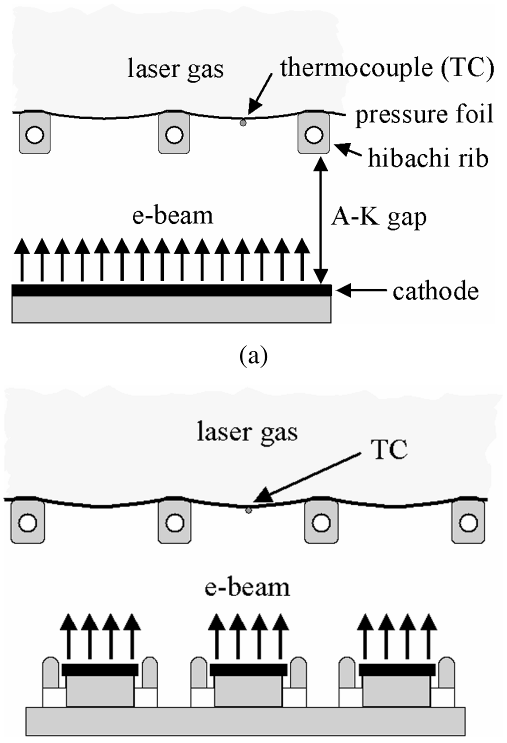
14. ABSTRACT

This paper presents experimental results of the foil temperature on the rep-rated electron beam pumped KrF laser during 50-shot bursts at 1 Hz and 5 Hz. The experiments demonstrate improved convective cooling of the foil during repetitive operation by confining the recirculating laser gas to flow along the hibachi foils.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**4**	

the gas velocity along the foil to ~ 2.5 times the unperturbed gas velocity. Actuated louvers cycle between the closed and open louver positions between shots: 100 ms in the closed position, then in the open louver position for 100 ms @ 5 Hz, or 900 ms @ 1 Hz.



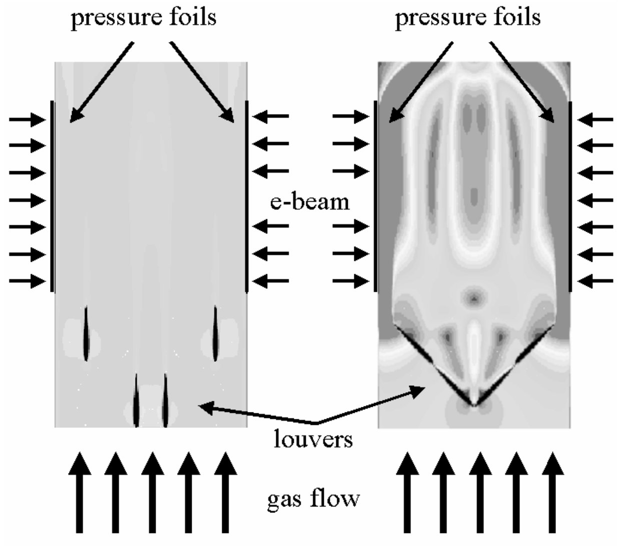
(a)

(b)

Figure 1. Configuration of the foil temperature setup with: (a) monolithic cathode and (b) strip cathode. The A-K gap ranged from 3.5 cm for a strip cathode to 5.2 and 5.7 cm for a monolithic cathode.

III. EXPERIMENTAL RESULTS

The temperature of the 25 µm thick SS foil rises to 480°C after a short 15 shot burst at 5 Hz without the recirculation of the gas in the laser cell (see Fig. 3, trace a). The foil temperature does not increase linearly above 300°C indicating contributions from radiation and uncontrolled free convective cooling. With forced convective cooling driven by a more uniform gas velocity of 7.5 m/sec, the foil temperature is limited to 430°C (open louver position, Fig. 3, trace b). By actuating the louvers, and thus, temporarily closing the louvers for 100 ms between each shot, the temperature decreases to 325°C (see Fig. 3, trace c). Actuated louvers are cycled only once per shot. After the 50 shot burst, louvers are held in the open position. Therefore, at $t > 10$ sec the temperature decay of trace (c) matches that of trace (b). With louvers maintained in a fixed closed position, the foil temperature is further reduced to 265°C (ses Fig. 3, trace d).



(a) (b)

Figure 2. Cooling mechanism of the pressure foil. (a) the laser gas flow is quiescent with open louvers, and (b) the laser gas velocity is enhanced at the vicinity of the pressure foil with closed louvers.

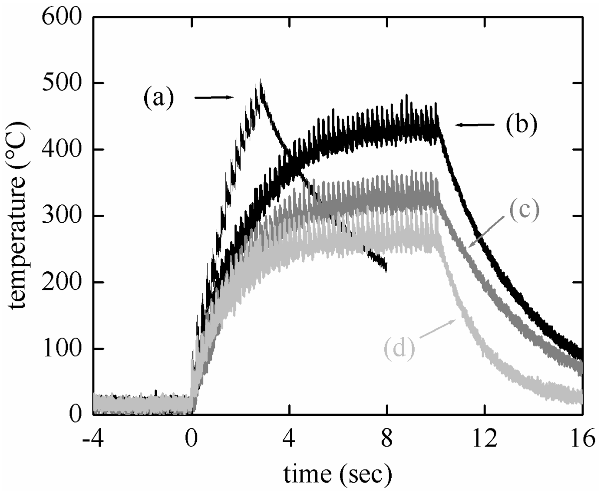


Figure 3. Foil temperature vs. louver position, with a monolithic cathode: (a) 15 shots @ 5 Hz with 1 atm of Ar in the laser cell and no gas flow, reaching an average temperature of 480°C on the last shot, (b) 430°C with open louvers, (c) 325°C with actuated louvers, and (d) 265°C with closed louvers. Last 3 cases show 50 shots each @ 5 Hz with 1.5 atm of Ar and an average gas velocity of 7.5 m/sec when louvers are open.

Reducing the volumetric heating rate of the foil by a factor of 5 (from 5 Hz to 1 Hz e-beam operation) significantly lowers the foil temperature. With actuated louvers, an average gas velocity of 5 m/sec, and the e-beam emitted from a monolithic cathode, the foil reaches a temperature of 430°C @ 5 Hz and 155°C @ 1 Hz operation (see Fig. 4). The foil temperature does not decrease by a factor of 5 because the close-to-open duty cycle of the actuated louvers changes from 50%-50% @

5 Hz to 10%-90% @ 1 Hz. Furthermore, the effect of radiation cooling cannot be neglected at higher foil temperatures.

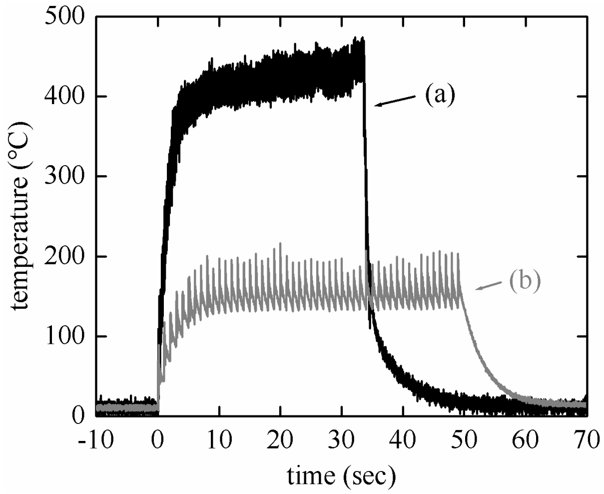


Figure 4. Foil temperature vs. shot rep rate, with a monolithic cathode, 1 atm of Ar in the laser cell, an average gas velocity of 5 m/sec, and louvers actuated: (a) 169 shots @ 5 Hz reaching 430°C and (b) 50 shots @ 1 Hz reaching 155°C.

To meet the requirements for laser efficiency, the e-beam is partitioned into strips on the cathode. This minimizes the number of electrons striking the hibachi ribs thus increasing the electron energy deposition in the laser gas. The strip cathode has the same total diode current as the monolithic cathode. A shorter A-K gap increases the e-beam current density to compensate for the smaller emitting area of a strip cathode. The strip cathode results (see Fig. 5) show the same trends as with the monolithic cathode; high foil temperatures at 5 Hz operation that decrease with lower e-beam rate-rates. Due to the higher current density of the strip cathode, which leads to a higher volumetric foil heating rate, the foil temperature reaches 530°C @ 5 Hz and 200°C @ 1 Hz. This is an increase of 23% @ 5 Hz and 29% @ 1 Hz compared to the monolithic cathode with otherwise identical gas flow and louver conditions. The proportionally lower foil temperature @ 5 Hz for the strip cathode can be attributed to radiation cooling.

Larger gas velocities in the laser cell increase the mass flow at the foils and enhance forced convective cooling. Figure 6 shows that the foil temperature decreases from 350°C to 325°C and 315°C by increasing the average gas velocity from 6.2 m/sec to 7.5 and 8.4 m/sec, respectively. A foil cooling model that incorporates convection, conduction, and radiation cooling as well as louver configuration and gas flow is currently under development.

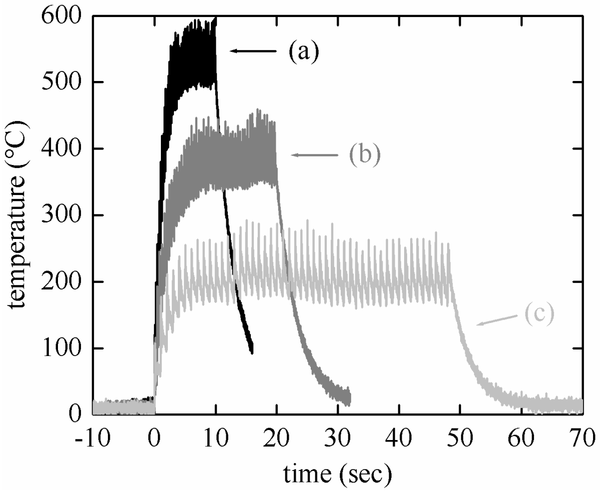


Figure 5. Foil temperature vs. shot rep rate, with a strip cathode, 1 atm of Ar in the laser cell, an average gas velocity of 5 m/sec, and louvers actuated: (a) 50 shots @ 5 Hz reaching 530°C, (b) 50 shots @ 2.5 Hz reaching 380°C, and (c) 50 shots @ 1 Hz reaching 200°C.

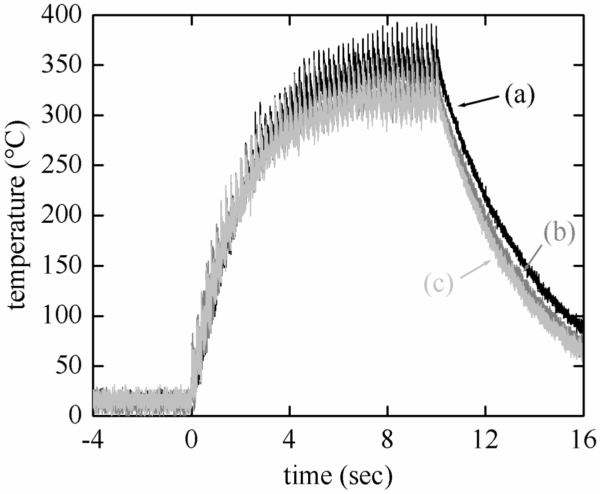


Figure 6. Foil temperature vs. average gas velocity, with a monolithic cathode, 1.5 atm of Ar in the laser cell, 50 shots @ 5 Hz, and louvers actuated: (a) 350°C at 6.2 m/sec, (b) 325°C at 7.5 m/sec, and (c) 315°C at 8.4 m/sec.

The measurements presented above use pure argon in the laser cell. A KrF laser operates with a gas mixture that includes 20-40% Kr, 0.3-0.5% F_2, and the remainder being Ar. The total thermal conductivity of an Ar/Kr gas mixture is reduced compared to a case with pure Ar since krypton has only half of the thermal conductivity of argon. The addition of Kr will also slightly increase the volumetric heating rate of the foil. Its larger atomic number allows for more electrons to scatter from the laser gas back into the vacuum diode, and thus, depositing more electron energy in the pressure foil [5]. Both effects lead to higher foil temperatures. With a 40% Kr and 60% Ar mixture at a total pressure of 1.36 atm, the foil reaches 410°C (see Fig. 7, trace a), which is significantly higher than 325°C for the pure Ar case at 1.5 atm (see Fig. 6, trace b). Both cases have a gas velocity of 7.5 m/sec and louvers are actuated. Adding a small amount of helium to the Kr/Ar gas mixture increases the total thermal conductivity of the gas. With 10% of He, the foil temperature is reduced to 330°C (see Fig. 7, trace b), and with 17% of He, the temperature is further reduced to 310°C (see Fig. 7, trace c).

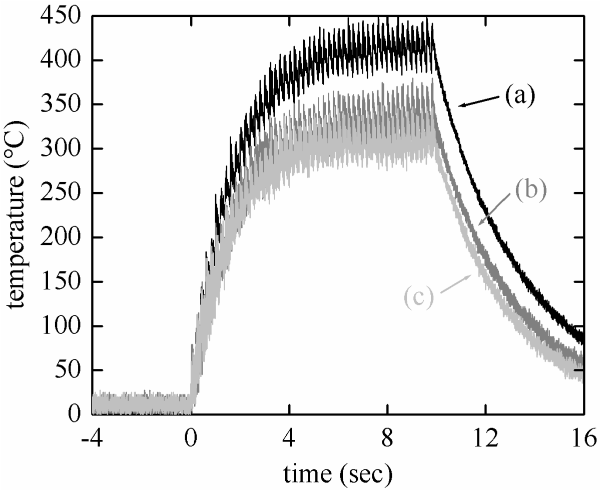


Figure 7. Foil temperature vs. laser gas mixture, with a monolithic cathode, an average gas velocity of 7.5 m/sec, 50 shots @ 5 Hz, and louvers actuated: (a) 410°C with 8 psi Kr and 12 psi Ar in the laser cell, (b) 330°C with 8 psi Kr, 12 psi Ar, and 2.3 psi He, and (c) 310°C with 8 psi Kr, 12 psi Ar, and 4 psi He.

IV. DISCUSSION

Thermocouple measurements of the pressure foil indicate that enhanced turbulent gas flow is required for effective forced convective cooling. It calls for a high average gas velocity of at least 8.4 m/sec in the laser cell as well as for louvers, located upstream of the foils, that redirect the gas flow towards the foil and locally increase increase the gas velocity. To compensate for the low thermal conductivity of krypton, a small percentage of helium could be added to the laser gas mixture. Although actuated louvers that temporarily close between shots are to some extent effective in limiting the foil temperature, optimal results for cooling are obtained when the louvers are fixed in the closed position. The effect of the resulting turbulence on the KrF laser profile will be investigated in the future.

In addition, future work will explore techniques to lower the foil temperature using a combination of convective and conduction cooling methods. This requires a new hibachi structure with high thermal conductance ribs and a sufficient water flow rate through the cooling channel. The foil properties should include high tensile strength, high thermal conductivity as well as low fluorine reactivity. An aluminum/titanium/aluminum sandwich and AlSiC (i.e., aluminum with silicon carbide) are two foil materials currently under investigation.

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, Nov. 2004.

[3] F. Hegeler, M. C. Myers, M. F. Wolford, M. Friedman, J. Giuliani, J. D. Sethian, D. Weidenheimer, D. Morton, and L. Schlitt, "Electra: A repetitively pulsed KrF laser system," Proc. of the 14th IEEE Intern. Pulsed Power Conf., 2003, pp. 97-102.

[4] F. Hegeler, M. Friedman, M. C. Myers, J. D. Sethian, and S. B. Swanekamp, "Reduction of edge emission in electron beam diodes," Physics of Plasmas, vol. 9, pp. 4309-4315, Oct. 2002.

[5] F. Hegeler, D. V. Rose, M. C. Myers, J. D. Sethian, J. L. Giuliani, M. F. Wolford, and M. Friedman, "Reduction of edge emission in electron beam diodes," Physics of Plasmas, vol. 11, pp. 5010-5021, Nov. 2004.