SCALLOPED HIBACHI AND VACUUM-PRESSURE FOIL FOR ELECTRA: ELECTRON BEAM PUMPED KrF LASER*

R. Jaynes+, T. Albert++, F. Hegeler++ and J. D. Sethian
Plasma Physics Division, Naval Research Laboratory
Washington, DC 20375 USA

Abstract

We are developing a new type of "scalloped" hibachi structure to be deployed on Electra, a 700 Joule/pulse electron beam pumped KrF laser system, to improve the durability and efficiency of the pressure foil. In an e-beam pumped laser, an electron beam is generated in a high vacuum diode, and then passed through a pressure foil to pump the gain medium in the gas laser cell. Previous hibachi structures used flat "picture frame" topologies in which the foil is laid flat on the frame. The natural bulging of the foils under pressure introduces significant stress concentrations at the corners of the rib openings. In our new design, the hibachi frame is scalloped, so the foil between the ribs approximates a section of a cylindrical pressure vessel. This arrangement eliminates these stress concentrations and, because the stress can in principle be made purely cylindrical, lowers the overall stress as well. This allows use of a thinner foil to transport the e-beam more efficiently.

Two techniques were developed to seal this non-planar vacuum surface: utilizing a bonded gasket-foil fixture or employing a quad or double seal o-ring. The former is less expensive, but only proved viable for thicker foils. These methods have been shown to support foils of various materials including aluminum, stainless steel, and titanium with thicknesses ranging from 12 μm to 75 μm. Foils have been tested under high vacuum and with up to 30 psi differential applied to the foil.

I. INTRODUCTION

The Electra laser system at the Naval Research Laboratory is a repetitively pulsed electron beam pumped krypton fluoride (KrF) laser system that is being used to develop the science and technology for a durable and efficient laser driver for inertial confinement fusion energy (IFE) applications [1-8].

The foils are a critical part of this durability and efficiency. The electron beam, generated in a high vacuum diode, passes through a pressure foil to pump the gain medium in the gas laser cell. The foil must have a low enough areal density to allow the electron beam to pass through efficiently, but strong enough to withstand the pressure of the gas in the laser cell as well as the shock wave generated when the electron beam deposits its energy in that gas. Previous experiments at the Naval Research Laboratory have shown the e-beam can deposit up to 75% of its energy in the laser cell with a 1 mil (25 μm) thick Ti foil, where as 1 mil Stainless Steel 304 and 2 mil Ti foils allow up to 70% of the diode e-beam energy in to the laser gas [9]. These results were benchmarked against the Integrated Tiger Series (ITS) simulations. These experiments were carried out on the 500 kV Electra Main amplifier. For the smaller Electra preamplifier, the electron beam voltage is only 175 kV, which reduces the choices for foils to 1 mil Al or the equivalent. Since a 1 mil aluminum foil is relatively weak, we need to develop a more advanced hibachi to support it.

II. THE HIBACHI AND FOIL

Since the foil is not strong enough to span the whole distance of the laser cell, it is typically supported by a periodic rib structure, called a hibachi. Traditional, flat or 'picture frame' type hibachis will induce 3-D stresses in the corners of the rib openings when the foil is under pressure. The new scalloped hibachi presented in this paper reduces these stresses by allowing the foil to conform to a purely 2-D topology. This geometry does, however, provide a challenge of sealing to high vacuum conditions. In this paper we will examine two methods of sealing this scalloped hibachi: a gasket technique and a quad or double seal o-ring technique.

Figure 1 depicts a cutaway side view and dimensions of the new scalloped hibachi. The angle θ is 40 deg. The rib width is 0.225", the rib opening is 0.788" and R_{foil} is 0.535".

* Work supported by DOE/NNSA

+ Science Applications International Corp., McLean, VA 22102 USA
++ Commonwealth Technologies Inc., Alexandria, VA 22315 USA

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 2007	**N/A**	**-**

4. TITLE AND SUBTITLE **Scalloped Hibachi And Vacuum-Pressure Foil For Electra: 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 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., The original document contains color images.

14. ABSTRACT

We are developing a new type of scalloped hibachi structure to be deployed on Electra, a 700 Joule/pulse electron beam pumped KrF laser system, to improve the durability and efficiency of the pressure foil. In an ebeam pumped laser, an electron beam is generated in a high vacuum diode, and then passed through a pressure foil to pump the gain medium in the gas laser cell. Previous hibachi structures used flat picture frame topologies in which the foil is laid flat on the frame. The natural bulging of the foils under pressure introduces significant stress concentrations at the corners of the rib openings. In our new design, the hibachi frame is scalloped, so the foil between the ribs approximates a section of a cylindrical pressure vessel. This arrangement eliminates these stress concentrations and, because the stress can in principle be made purely cylindrical, lowers the overall stress as well. This allows use of a thinner foil to transport the e-beam more efficiently. Two techniques were developed to seal this non-planar vacuum surface: utilizing a bonded gasket-foil fixture or employing a quad or double seal o-ring. The former is less expensive, but only proved viable for thicker foils. These methods have been shown to support foils of various materials including aluminum, stainless steel, and titanium with thicknesses ranging from 12 ìm to 75 ìm. Foils have been tested under high vacuum and with up to 30 psi differential applied to the foil.

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**	**5**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

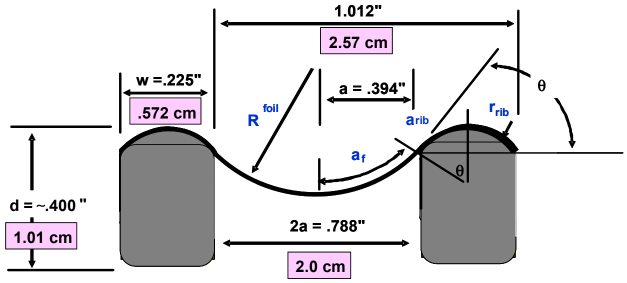


Figure 1. Example of a scalloped hibachi structure.

Table 2. Strength and density of foil materials

	Aluminum 5052	Stainless Steel 304	Titanium
Yield Strength	28,000 psi	29,500 psi	115,000 psi
Ultimate Strength	33,000 psi	74,000 psi	131,000 psi
Density	2.70 g/cm^3	8.00 g/cm^3	4.50 g/cm^3

In the scalloped hibachi, the stress is purely two dimensional. The maximum stress in a 2-D foil is calculated using the following equation:

$$S = \frac{pa}{t}\frac{1}{\sin\theta} \quad (1)$$

with the pressure 'p', width the foil spans '2a', thickness of the foil 't' and the angle θ which the foil makes between the foil and the top rib contact point [10].

Below are some calculations of maximum stresses in foils at 0.5, 1, and 2 mil thicknesses and for typical laser operating pressures of 1 atm, 1.5 atm, and 2 atm.

Table 1. Foil stress calculations for θ=40^o, a = 0.394".

Thickness (mils)	Stress at P = 1 atm	Stress at P=1.5 atm	Stress at P=2 atm
0.5	18009 psi	27014 psi	36018 psi
1	9005 psi	13507 psi	18009 psi
2	4502 psi	6753 psi	9005 psi

In Table 2, we compare the maximum stresses, calculated above to ultimate and yield strengths of materials we can use for foils. The titanium foil is by far the strongest, but it has a disadvantage in that it has been observed to be strongly reactive with fluorine at elevated temperatures. When considering foils for efficient energy transmission, to the first order, foil thickness times density can be compared to each other (i.e. 3 mil aluminum, 2 mil titanium and 1 mil stainless steel provide similar e-beam transport efficiencies). The 3 mil aluminum has much higher yield strength than 1 mil stainless steel, but since stainless steel is more ductile, due to the relative large difference between its ultimate and yield strength, it has been shown to be more durable on experiments with the Electra main amplifier. All three foils are investigated for use in the scalloped hibachi.

III. Experiment Setup and Procedure

A special test fixture was built as shown in Figure 2, to evaluate the vacuum seal of the scalloped hibachi. The foil is placed on a hibachi frame, in the center of this fixture, separating the top pressure cell from the lower vacuum cell. From the bottom of the fixture there is a vacuum line that goes to a BOC Edwards turbo pump model# ext 255H 24V. This pump is backed by an Anest oil free scroll vacuum roughing pump, model# isp-90. Ultimate vacuums were tested with a blank flange in place of the foil and found to be ~2E-2 Torr for the roughing pump, and ~2E-5 with the turbo pump. Above the foil is a 1" thick Lexan plate for adding additional pressure to load the foil, with compressed nitrogen up to 2 atmospheres (30 psia).

Figure 2. Picture of hibachi test fixture.

Figure 3, is a side view of the hibachi test fixture. Visible is a cross-section of the fixture along the scalloped direction. There are 5 ribs to support the foil. The foil spans a distance of 0.788" between the ribs, and the ribs are 0.225" thick. This gives a 77.7% optical transmission for the e-beam through the ribs. Electrostatic defocusing, scattering in the foil and back scatter from the laser gas cell will further decrease the total electron transmission.

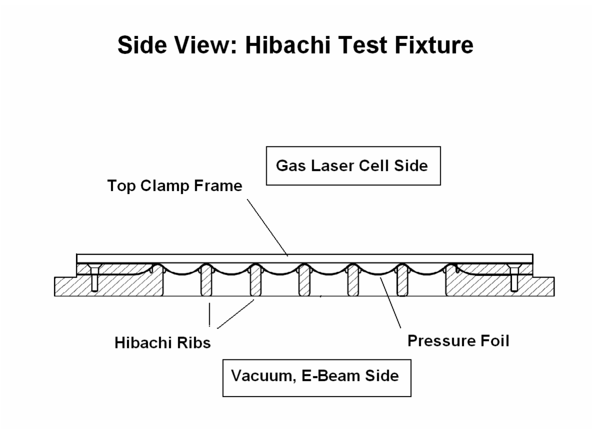
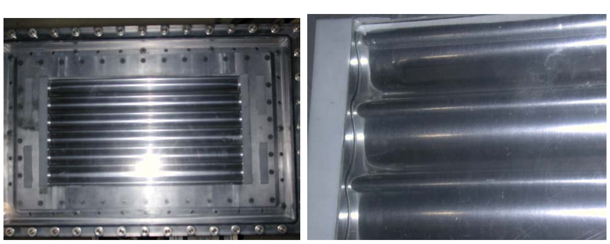


Figure 3. Side view of scalloped hibachi test fixture.

The test procedure is as follows: Once the foil is seated, the roughing pump is started and vacuum is monitored for about 1 hr. If the vacuum measures 2e-2 torr and the foil appears in good shape under atmospheric pressure, then the turbo pump is started and the foil is continuously monitored for vacuum leaks, or wrinkles and deformation that can lead to foil failures. If there is a good vacuum seal on the foil, the turbo pump will bring the vacuum down to a pressure of about 2e-5 torr, the ultimate pressure for the system. Next, the 1" thick Lexan plate is placed on top of the test fixture to allow the foil to be tested under pressure. Pressures up to 30 psi differential, can be added to load the foil. Initial testing of foil is always done with the roughing pump only, to verify foil integrity. Then more sensitive testing is done with the turbo pump. The turbo pump allows the foil to be checked for smaller vacuum leaks, which may not be noticed on the roughing pump.



(A) (B)

Figure 4. Aluminum foil in hibachi test fixture.
(A) Whole hibachi, (B) Close up of foil under pressure.

Figure 4(A) depicts an example foil under test in the test fixture. Before the foils are put under pressure there is some slack in the foil, which allows it to ripple a little. A close up view of the foil under pressure in Figure 4(B) shows that the foil becomes very taut and displays a two dimensional scalloped appearance.

We developed the following techniques to successfully seal the foil: In the first method, a gasket is bonded all around the foil as in a picture frame. The sealing side of the gasket is coated with Krytox vacuum grease, then the foil is placed in the hibachi frame. The gasket and foil are held in place from the top with a clamp frame, which is bolted through holes in the gasket to the hibachi frame. This top frame is precisely torqued to 18in-lb with screw spacing of 1.088" in. This applies a very uniform pressure to the gasket, which was found to be important for a good vacuum seal.

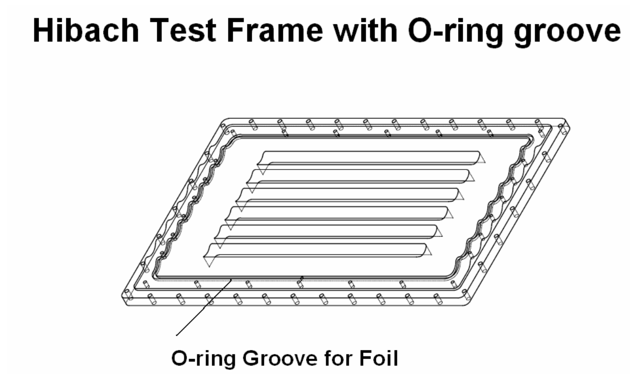


Figure 5. Perspective rendering of hibachi test fixture.

A second method of sealing the hibachi utilizes a quad or double seal o-ring in a scalloped o-ring groove. This o-ring is inserted in to the groove depicted in Figure 5. The 'X' shape of the quad or double seal o-ring provides additional sealing since it comes in contact with the foil on two surfaces. In addition the 'X' shape helps the o-ring stay wedged in the o-ring groove as it bends through the troughs and valleys of the scalloped hibachi. It was found that having the bottom of the o-ring groove with a round cross-section, as opposed to a square cross-section, aids in the sealing process since the double or quad seal o-ring seals on the sides of the o-ring grove as well. The rounded bottom surface also reduces manufacturing costs since a simple ball end mill can be used to cut this grove, even on complex scalloped surfaces. To make a square cross-section o-ring grove over a scalloped surface would require a five axis milling machine, or many passes with very small end mills. Thus the rounded cross-section o-ring grove aids in sealing the hibachi as well as reducing manufacturing costs.

The following are a summary of the different foils and methods used to seal the hibachi, and the results:

A. 25 µm Stainless Steel Foil and Gasket

The 25 µm (1mil) stainless steel foil was the easiest foil to seal. The Stainless steel is much stronger than the aluminum foil, and the stiffness of the foil keeps it from wrinkling under pressure. The steel foil is too thick to allow the electron beam to pass through at a reasonable efficiency for the Electra pre-amp hibachi, according to tiger simulation. This foil is not an option for the Electra pre-amplifier laser system unless it can be made pinhole free at thicknesses less than .00025", but is still an option for the main amplifier, since the e-beam voltage is significantly higher.

B. 75 µm Aluminum Foil and Gasket

The 75 µm (3 mil) aluminum foil was very easy to seal at 1 atmosphere of pressure. Again this foil is thick enough to make it stiff so it does not wrinkle when put under pressure. As with the stainless foils, this foil is too thick to be used on the hibachi of the pre-amplifier laser.

C. 25 µm Aluminum Foil and Gasket

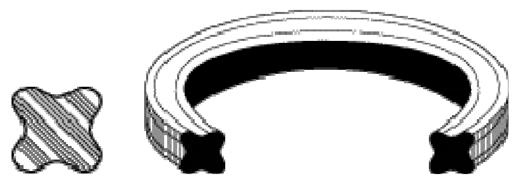
The 25 µm (1 mil) foil is thin enough to transmit the electron beam with reasonable efficiency through the foil, but the foil is so thin that it was difficult to clamp using the gasket method. This method allowed the foils to pull out under pressure, particularly at the ends. As a result the foils tended to be depressed into the corners of the rib openings, which lost the purely cylindrical stress. As a result the foils tended to wrinkle, and rupture at the corners of the end rib openings. Despite numerous attempts and fixes, the 1 mil aluminum foil was not able to be sealed using the gasket method but the double or quad seal o-ring was able to easily seal this foil.

D. 12 µm mil Etched Titanium Foil and Gasket

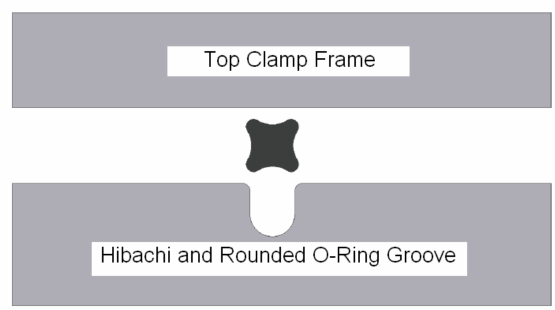
The titanium foil is much stronger than the aluminum, having a yield strength of 115,000 psi, compared to aluminum with a yield strength of 28,000 psi, so a thinner titanium foil will have enough strength to span the ribs without breaking. Since there are no commercially available foils that are rolled to a thickness of 12 µm and wide enough to fit the size of the laser cell, these foils were created by etching 25 µm titanium foils down to the thickness of 12 µm. These foils are very thin and have very little stiffness, which allows the foils to bend and wrinkle very easily. Even though these thin foils did deform under pressure, they did not rupture due to their superior strength and were successfully tested with 25 psi differential pressure.

E. Quad or Double Seal O-Ring

The quad or double seal o-ring was able to seal the most difficult foil, the 25 µm (1 mil) aluminum foil, where the gasket method was not. The cross-section of a quad or double seal o-ring is depicted in Figure 6(A). In Figure 6(B) shows the double or quad seal o-ring with the rounded o-ring groove below and clamp frame above. The foil will seat between the top of this o-ring and the bottom of the clamp frame. This configuration is able to hold the foil more tightly than the gasket configuration, and thus keeps the stresses purely cylindrical. This arrangement successfully sealed 25 µm aluminum foil, with 30 psi differential pressure. This will be the method used to seal the foil on the pre-amp scalloped hibachi.



(A)



(B)

Figure 6. (A) Cross-sectional view of a quad or double seal o-ring and cut away view of o-ring. (B) Cut away view of quad or double seal o-ring with rounded o-ring groove below and clamp frame above.

IV. CONCLUSION

The scalloped shaped hibachi is a novel hibachi design that will reduce stresses and increases durability and efficiency of a hibachi pressure foil of an e-beam pumped laser system. This reduction of stress is realized by the special scalloped shaped hibachi structure that forces the foil to conform to a purely 2 dimensional surface, thus alleviating wrinkles and higher stresses associated with 3-D deformation of the foil. Two methods were investigated to seal this non-conventional vacuum surface, a gasket method, and a quad or double seal o-ring method. The quad or double seal o-ring method was found to be superior because it was able to more tightly clamp the foil, and prevent the foil from losing its purely cylindrical stress.

V. ACKNOWLEDGEMENTS

The authors acknowledge the advice from A.E. Robson who originally proposed the scalloped hibachi, and R. Jones for work and technical support on this experiment.

VI. REFERENCES

[1] W. R. Meier, "Osiris and SOMBRERO inertial fusion power plant designs-summary, conclusions, and recommendations," Fusion Engineering and Design, vol. 25, pp. 145-157, August 1994.

[2] G. J. Linford, D. E. Driemeyer, S. W. Fornaca, and A. W. Maschke, "Design descriptions of the Prometheus-L and -H inertial fusion energy drivers," Fusion Engineering and Design, vol. 25, pp. 111-124, August 1994.

[3] J. D. Sethian, S. P. Obenschain, R. H. Lehmberg, and M. W. McGeoch, "A rep rate KrF system to address issues relevant to inertial fusion energy," Fusion Engineering and Design, vol. 44, pp. 371-375, March 1999.

[4] I. Okuda, e. Takahashi, and Y. Owadano, "A conceptual design of a high-efficiency rep-rated pulsed power system for KrF laser drivers of inertial fusion energy ," Applied Physics B (Lasers and Optics), vol B71, pp. 247-250. August 2000.

[5] 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, S. Searles, "Electron beam pumped KrF lasers for fusion energy," Physics of Plasmas, vol. 10, pp. 2142-2146, May 2003.

[6] J. D. Lindl, B. A. Hammel, B. G. Logan, D. D. Meyerhofer, S. A. Payne, and J. D. Sethian, "The US inertial confinement fusion (ICF) ignition programme and the inertial fusion energy (IFE) programme," Plasma Physics and Controlled Fusion, vol 45, pp. A217-234, December 2003.

[7] J. D. Sethian, M. Friedman, R. H. Lehmberg et al., "Fusion energy with lasers, direct drive targets, and dry wall chambers ," Nuclear Fusion, vol.43, pp. 1693-1709, December 2003.

[8] F. Hegeler, M. C. Myers, M. F. Wolford, J. D. Sethian, R. Jaynes, P. Burns, M. Friedman, J. L Giuliani, T. Albert, and J. Parish, "The Electra KrF Laser System," 2007 IEEE Pulsed Power and Plasma Science Conference, Albuquerque, NM, June 2007.

[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, Nov. 2004.

[10] A. E. Robson, private communications.