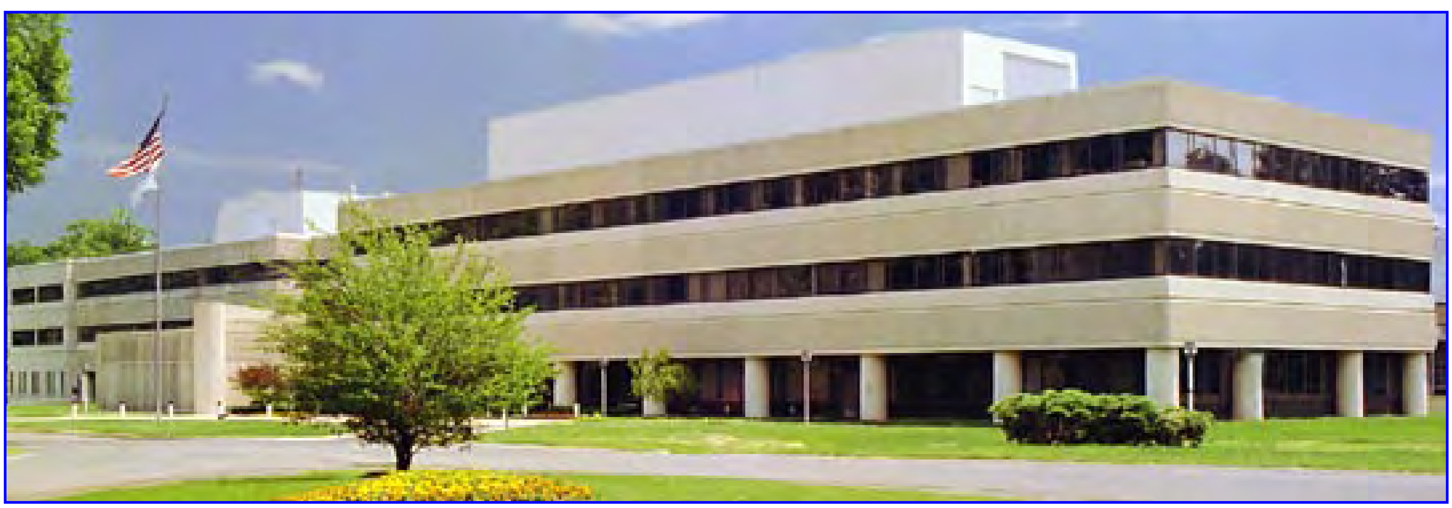
Princeton Plasma Physics Laboratory

PPPL-4147
PPPL-4147

Design and Numerical Stress Analysis of Silicon Membrane Hibachi Windows

Chang H. Jun, Charles Gentile,
Craig Priniski, and John Sethian

February 2006



Prepared for the U.S. Department of Energy under Contract DE-AC02-76CH03073.

Princeton Plasma Physics Laboratory
Report Disclaimers

Full Legal Disclaimer

Trademark Disclaimer

PPPL Report Availability

Princeton Plasma Physics Laboratory

This report is posted on the U.S. Department of Energy's Princeton Plasma Physics Laboratory Publications and Reports web site in Fiscal Year 2006.

The home page for PPPL Reports and Publications is:

http://www.pppl.gov/pub_report/

Office of Scientific and Technical Information (OSTI):

Available electronically at: http://www.osti.gov/bridge.

Available for a processing fee to U.S. Department of Energy and its contractors, in paper from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062

Telephone: (865) 576-8401

Fax: (865) 576-5728

E-mail: reports@adonis.osti.gov

Design and Numerical Stress Analysis of Silicon Membrane Hibachi Windows

Chang H. Jun[a], Charles Gentile[a], Craig Priniski[a], John Sethian[b]

[a] *Princeton Plasma Physics Laboratory, Princeton NJ, U.S.A.*

[b] *Naval Research Laboratory, Washington D.C., U.S.A.*

***Abstract*—A silicon membrane windows is developed for a KrF laser system. The main function of the windows is to pass electron beam into the laser cell and to hold pressurized gas in the cell. 150 micro-meter thick silicon windows successfully survived from heated electron beam bombardment and shows 80% of electron beam transmission rate. The single silicon windows endured 250,000 cycles of electron beam shots. The arrayed windows did not show sufficient performance due to excessive heat generation. To enhance the longevity, the cooling system has to be improved and a study of the arc generated by the cathode is necessary.**

Keywords: Silicon Window, KrF laser, Electron beam, Transmission rate, Corrosion by gas, Diamond coating.

I. Introduction

This project involves developing silicon windows which are used on the Electra laser under development at the Naval Research Laboratory. The laser is an Electra Krypton Fluoride (KrF) laser (wave length is 248nm) and it is similar to the Nike KrF laser. The laser operates at 750keV and will be used as a direct driver of the Inertial Fusion Energy (IFE) project. The IFE project is supported by the U.S. department of Energy purpose of achieving a fusion reaction by radially focussing many laser beams in a large (R=11m) spherical chamber. The window is an essential component to generate the laser beams. A single window membrane is approximately 50mm in diameter and it is installed as several groups between the laser cell and the cathode which is the electron beam source. The electron beams are transmitted through the window into the laser cell containing KrF gas to stimulate the laser.

A. Transparent and Gas Pressure Barrior Simultaneously

To confine the KrF gas in the laser cell, any kind of wall would be sufficient, but to achieve laser stimulation, some part of the wall has to allow electron beam transmission through it. The window serves this purpose while it simultaneously confines the pressurized gas in the laser cell.

B. High Mechanical Strengh and High Transmission Rate

The window has to be strong enough to withstand the gas pressure and high temperature of the KrF, and also it has to allow for electron beam penetration. The design difficulty is to satisfy these two opposite requirements. One condition requires having thick windows to survive and another condition requires a very thin thickness to maximize electron beam transmission.

This article is supported by The Naval Research Laboratory.

II. Design Requiment

A. Transmission Rate of At Least 80%: Silicon is chosen.

The window is installed between the cathode plate (in Figure 1, wide plate in front of pulsed power system) and the laser cell which contains KrF gas. The window has to pass at least 80% the electron beams through it. The transmission rate is critical to obtain high laser reaction probability in the cell. To realize this condition, many different materials were examined like titanium foil, stainless foil, etc. Silicon material was chosen as the final material due to it's low atomic number, high heat capacitance and high heat conductivity. Silicon shows very high mechanical strength compared to other materials when it is very thin. The low atomic number (z=14) guarantees high transmission rate because of small number and size of atom. High heat capacitance reduces the temperature rise which weakens the mechanical strength of any material. High heat conductivity is also a key characteristic to conduct away the generated heat. The window membrane is very thin, therefore heat conduction is slow due to limited heat conduction path and its geometric shape.

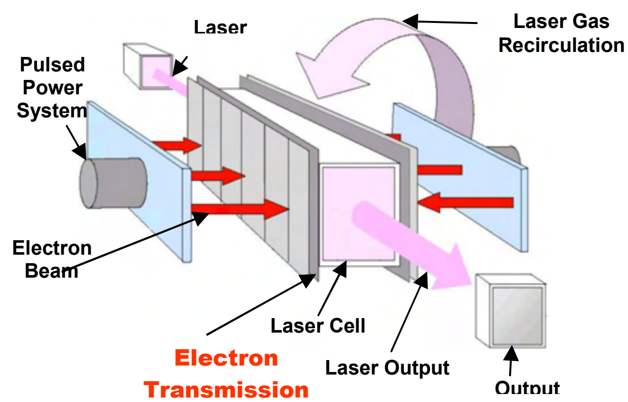


Figure 1. Key Components of the KrF Laser Amplifier.

B. 2.33atm Pressure Difference & 400C temperature

The window has to maximize electron beam transmission, but simultaneously has to block and confine the laser gas. The beams are pulsed at a rate of 5Hz from the vacuum side and the gas pressure is slightly over 2 bar. Therefore the pressure gap between two sides of the window is 2.33 bar. Temperature will asymptotically rise up to 400C as the heat load is continuously pulsed at 5Hz. In this mode of operation windows must survive for a minimum of 100M pulses or more than 5,000 hours (230 days) if it operates without rest. The experimental data and equations have been reviewed to determine the proper thickness of the silicon windows. We found that 150micro-meter (0.15mm) thickness silicon guarantees at least 80% transmission rate of the electron beams if the surface is flat and well finished. Because of the non-uniform conditions of experiment and other variables, the theoretical equation used for the analysis could not be exact. And, of course, the transmission rate is also related to the applied beam energy. To approximately model this for a 750 keV case, the following variables were used:

$$\frac{N_x}{N_o} = \exp[-\lambda x] \qquad (1)$$

No: Number of Electrons from Cathode

Nx: Number of Penetrated Electrons.

x: Thickness of Material.

λ: Penetrating Constant depending on Material and Electron Beam Energy. This case, around 1,000.

III. CONFIGURATIONS AND ANALYSIS

The electron beam transmission area is around 30cm*100cm and rectangular in shape. By the previous study, we recognized that we cannot afford to supply this as one big piece of thin silicon foil membrane because of Silicons' weak mechanical strength and the cooling problem. So we decided to put around 50 small windows on a big aluminum frame. Each window has approximately 40mm*40mm area. The minimum transmission rate of 80% was calculated as the value after considering the beam loss on the supporting grid. Between the small windows, a cooling pipe will pass to remove the heat generated from electron beam bombardment on the support grid and edge conducted heat from the Silicon.

Therefore, at first, engineering was required for each single window to guarantee the mechanical and thermal strength while showing an 80% transmission rate. The next step was to design and analyze a whole plate which will accommodate 48 windows and the cooling system. To determine the shape of the small windows, many different ideas were suggested and fabricated. The primary concern was that the flat surface of the 0.15mm silicon membrane with 40mm* 40mm area would not survive the 100M pulses of the electron beam. And also the thin surface hampers heat transmission by conduction. At the 400C temperature range, the radiation is not dominant, so the main cooling will be conduction from windows to the water cooled frames.

A. *"Ribs and Panes" Window Structure*

Ribbed rectangular surfaces are designed. The thick rib will sustain mechanically and the panes which are much less thick than 0.15mm will penetrate electron beams more than 80%. Another idea is similar than ribbed pane structure but rib shape is changed as honeycomb to reduce stress concentration on the crossed corner of ribs. The numerical analysis result shows quite reasonable stress values. The window is fabricated by a company according to suggested design.

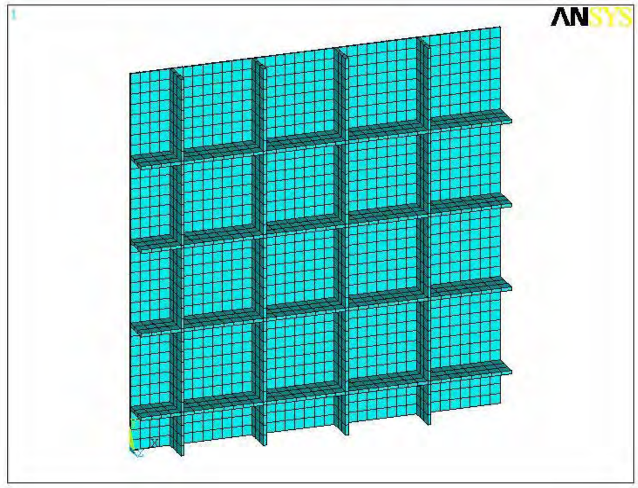


Figure 2. FEM model to analyze ribbed window.

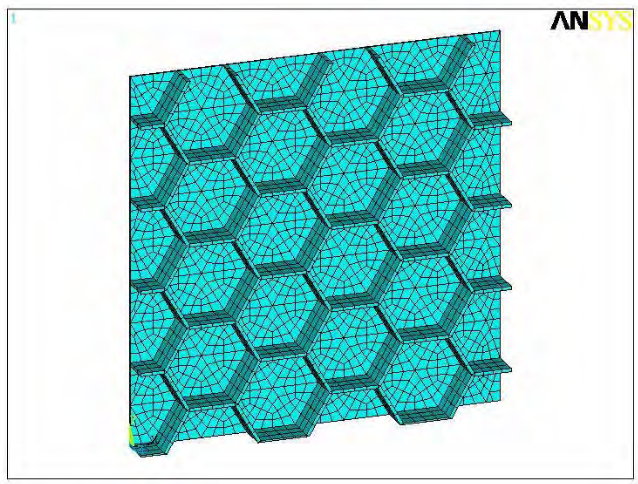


Figure 3. FEM model of honeycomb window.

The fabrication company used a chemical etching (chem-milling) process to make the rib and pane structure window. They mask the rib part and start the etching process to remove material in the pane. To guarantee the uniform thickness of panes, they coated a side of the silicon and glued with another silicon plate. The coated surface is inside the silicon material and it resists etching, so when etching chemical arrives at this area, the coating layer will not allow easy surface corrosion. By this coated area etching time is not very sensitive to the processing time. On inspection, the surface was excellent, but the ribs have problems on the bottom parts.

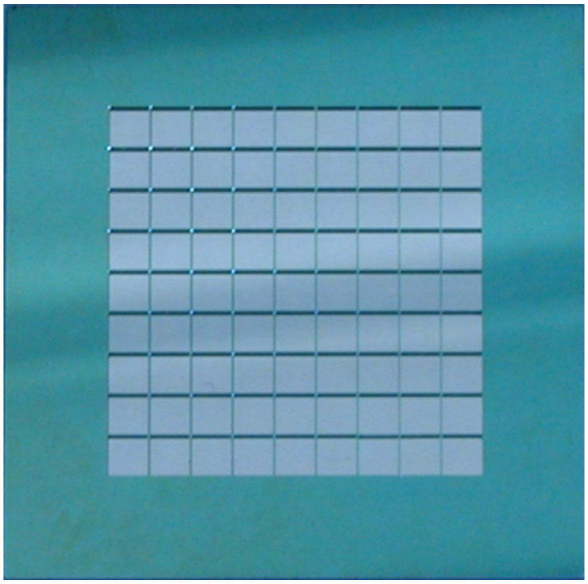


Figure 4. Fabricated silicon window with ribs and panes. (one pane is 1mm*1mm size)

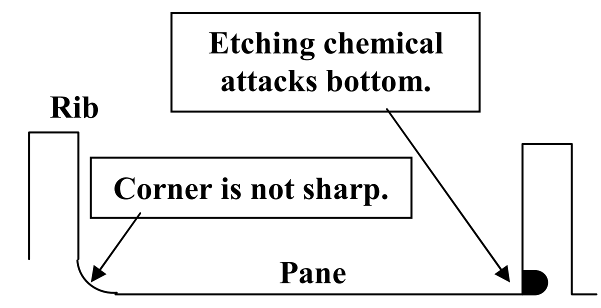


Figure 5. Inspected silicon surface after etching without coating (Left rib) and after coated etching (Right rib).

If the coated layer technique is not used, the etching process could not make sharp rib corner edges on the bottom. This rounded area significantly reduces the transmission rate. On the other hand, when the coating layer is applied, the pane surface quality is excellent, but the etching chemical attacked the bottom of the ribs. If the ribs have a weak connection with the panes, their mechanical strength will not be adequate for the internal gas pressure. Therefore, we concluded "ribs and panes" structure is not the proper geometry due to fabrication complexity.

B. Spherical and Circular Window Without Ribs

A spherical structure was examined and analyzed to verify the stress due to pressure. It shows very low stress but we could not locate a fabrication company with reasonable price and processing quantity within the time period required. Finally, we chose a disk shaped window. We tested this configuration with a very careful sealing installation around the disk window. Because of the high temperature, the sealing must accomodate a relatively large thermal expansion. A Room-Temperature Vulcanizing (RTV) seal was applied due to its good elasticity and its ability to reduce mechanical stresses due to thermal expansion.

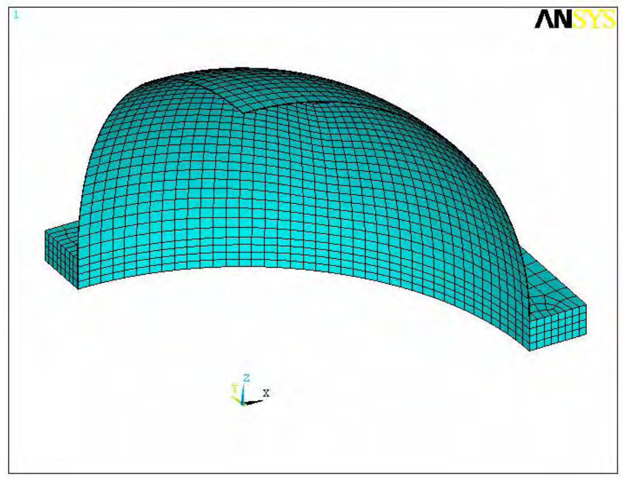


Figure 6. A hemi-spherical shape widow FEM modelhaving 10mm radius.

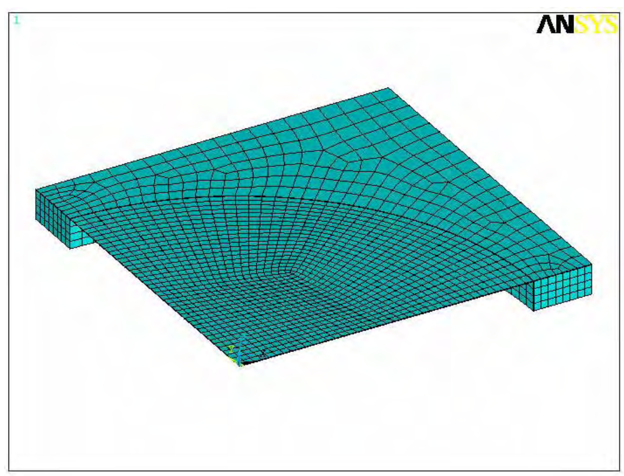


Figure 7. A disk shape widow FEM model having 10mm radius.

IV. Corrosion Protection

The KrF gas in the laser cell erodes the silicon window surface. The corrosion is acute and chronic also. To avoid this corrosion, we performed diamond coating on the laser gas side of the window. Repeated deflection test was also performed for 50k cycles to verify the coating quality. The experiment verified that very uniform and thin coating (t=1.2micro-meter) does not reduce transmission rate of electron beams. Several fatigue test and transmission rate test were also done. These tests showed reasonable results in view of the design goals.

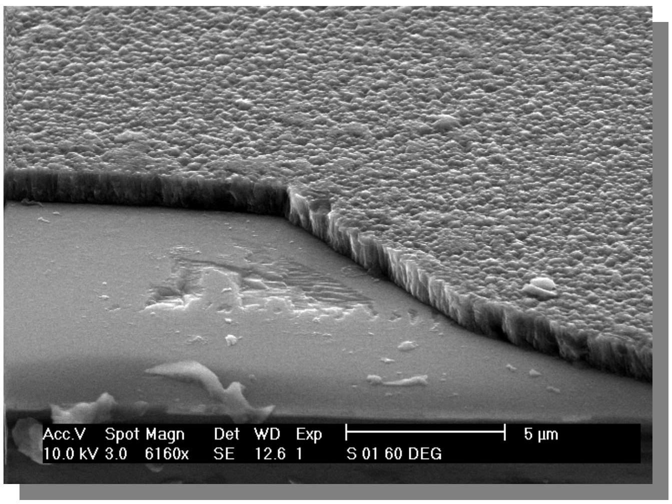


Figure 8. Diamond coated layer on the silicon plate.

V. Arrayed Window

After performing experiments with a single window, an aluminum plate was designed with cooling system. The frame is divided in two for one 30cm*100cm cathode. Each frame accommodates 24 silicon windows. The experiments were done to verify cooling and longevity of the windows.

Several windows were broken in the very early stage of the experiment which passed only several hundred shots of electron beams.

Breakdown of the cathode plate happened and temperature went up too high. We observed that the cooling method was not adequate and we needed a more stable cathode to protect the windows.

We also anticipated that arcs will occur between the cathode and silicon plate which is the anode part of the system. as a result, a more accurate understanding of the role and pattern of the electric arc is still necessary.

VI. Results

We obtained 0.5M cycles of longevity for a single silicon window. But we achieved only 180 cycles of longevity for the arrayed window. In the arrayed window, if only one window fails, the function of whole system compromised due to the laser gas leakage. While the current results are far from the required specification (100M cycles), we think we can achieve this goal for a single window in the near future. For the arrayed windows, more cooling analysis and testing are needed.

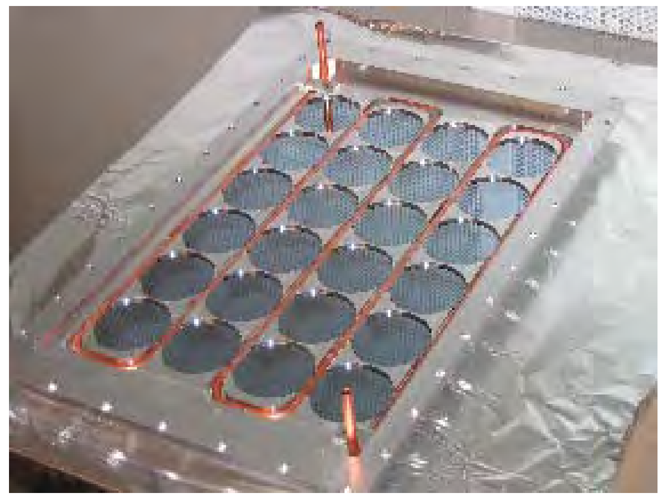


Figure 9. Aluminum frame and 24 arrayed windows (aperture is 38mm)

Acknowledgement

This work is supported by The Navel Research Laboratory (NRL) collaboration with The Princeton Plasma Physics Laboratory which is one of The U.S. Department of Energy's research establishments.

References

[1] J. Sethian, M. Friedman, J. Giuliani, et al, "Fusion Electra: A Krypton Fluoride Laser for Fusion Energy," Presented at the Inertial Fusion Sciences and Applications conference, Kyoto, Japan, 10-15 Sep 2001. fusion application parameters

[2] 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," *Physics of Plasmas,* Vol. 11, No. 11, pp. 5010-5021, (November 2004). strips

[3] C.A. Gentile, H.M. Fan, R.J. Hawryluk, F. Hegeler, et al, "Development of a Silicon Based Electron Beam Window For Use In a KrF Laser System," Presented at the second IAEA Technical Meeting on Physics and Technology of IFE Targets and Chambers, San Diego, 17-19 June 2002.

External Distribution

Plasma Research Laboratory, Australian National University, Australia
Professor I.R. Jones, Flinders University, Australia
Professor João Canalle, Instituto de Fisica DEQ/IF - UERJ, Brazil
Mr. Gerson O. Ludwig, Instituto Nacional de Pesquisas, Brazil
Dr. P.H. Sakanaka, Instituto Fisica, Brazil
The Librarian, Culham Science Center, England
Mrs. S.A. Hutchinson, JET Library, England
Professor M.N. Bussac, Ecole Polytechnique, France
Librarian, Max-Planck-Institut für Plasmaphysik, Germany
Jolan Moldvai, Reports Library, Hungarian Academy of Sciences, Central Research Institute for Physics, Hungary
Dr. P. Kaw, Institute for Plasma Research, India
Ms. P.J. Pathak, Librarian, Institute for Plasma Research, India
Dr. Pandji Triadyaksa, Fakultas MIPA Universitas Diponegoro, Indonesia
Professor Sami Cuperman, Plasma Physics Group, Tel Aviv University, Israel
Ms. Clelia De Palo, Associazione EURATOM-ENEA, Italy
Dr. G. Grosso, Instituto di Fisica del Plasma, Italy
Librarian, Naka Fusion Research Establishment, JAERI, Japan
Library, Laboratory for Complex Energy Processes, Institute for Advanced Study, Kyoto University, Japan
Research Information Center, National Institute for Fusion Science, Japan
Professor Toshitaka Idehara, Director, Research Center for Development of Far-Infrared Region, Fukui University, Japan
Dr. O. Mitarai, Kyushu Tokai University, Japan
Mr. Adefila Olumide, Ilorin, Kwara State, Nigeria
Dr. Jiangang Li, Institute of Plasma Physics, Chinese Academy of Sciences, People's Republic of China
Professor Yuping Huo, School of Physical Science and Technology, People's Republic of China
Library, Academia Sinica, Institute of Plasma Physics, People's Republic of China
Librarian, Institute of Physics, Chinese Academy of Sciences, People's Republic of China
Dr. S. Mirnov, TRINITI, Troitsk, Russian Federation, Russia
Dr. V.S. Strelkov, Kurchatov Institute, Russian Federation, Russia
Kazi Firoz, UPJS, Kosice, Slovakia
Professor Peter Lukac, Katedra Fyziky Plazmy MFF UK, Mlynska dolina F-2, Komenskeho Univerzita, SK-842 15 Bratislava, Slovakia
Dr. G.S. Lee, Korea Basic Science Institute, South Korea
Dr. Rasulkhozha S. Sharafiddinov, Theoretical Physics Division, Insitute of Nuclear Physics, Uzbekistan
Institute for Plasma Research, University of Maryland, USA
Librarian, Fusion Energy Division, Oak Ridge National Laboratory, USA
Librarian, Institute of Fusion Studies, University of Texas, USA
Librarian, Magnetic Fusion Program, Lawrence Livermore National Laboratory, USA
Library, General Atomics, USA
Plasma Physics Group, Fusion Energy Research Program, University of California at San Diego, USA
Plasma Physics Library, Columbia University, USA
Alkesh Punjabi, Center for Fusion Research and Training, Hampton University, USA
Dr. W.M. Stacey, Fusion Research Center, Georgia Institute of Technology, USA
Director, Research Division, OFES, Washington, D.C. 20585-1290

The Princeton Plasma Physics Laboratory is operated
by Princeton University under contract
with the U.S. Department of Energy.

Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2750
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
Internet Address: http://www.pppl.gov