

IFE Final Optics and Chamber Dynamics Modeling and Experiments

Final Technical Report

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Our OFES-sponsored research on IFE technology originally focused on studies of grazing-incidence metal mirrors (GIMM's). After the addition of GIMM research to the High Average Power Laser (HAPL) program, our OFES-sponsored research evolved to include laser propagation studies, surface material evolution in IFE wetted-wall chambers, and magnetic intervention. In 2003, the OFES IFE Technology program was terminated. We continued to expend resources on a no-cost extension in order to complete student research projects in an orderly way and to help us explore new research directions. Those explorations led to funding in the field of extreme ultraviolet lithography, which shares many issues in common with inertial fusion chambers, and the field of radiative properties of laser-produced plasma.

Our research from 1999 through 2006 led to numerous journal articles and conference publications. Our progress can be best described through these publications, which are listed below. Consistent with the phases of research listed above, the publications are broken into the following categories:

- A. IFE final optics
- B. Laser propagation physics in IFE chambers
- C. Aerosol generation and transport in IFE chambers
- D. Charged particle transport and magnetic diversion
- E. Radiative properties of laser-produced plasma
- F. EUV lithography
- G. General publications on IFE

A. IFE final optics

M. S. Tillack, S. A. Payne, N. M. Ghoniem, M. R. Zaghoul and J. F. Latkowski, "Damage threats and response of final optics for laser-fusion power plants," *Inertial Fusion Science and Applications 2001*, Kyoto Japan, Sept. 2001, 717-721.

T. K. Mau, M. S. Tillack, and M. R. Zaghoul, "Modeling of Mirror Surface Damage Effects on Beam Propagation in a Laser-Driven IFE Power Plant," *Proc. 19th IEEE/NPSS SOFE*, Atlantic City NJ, Oct. 2-5, 2001.

M. R. Zaghoul, M. S. Tillack, and T. K. Mau, "Sensitivity of Metal Mirrors to Laser-Induced Damage Under Long-Term Exposure at Shallow Angle of Incidence," *Proc. 19th IEEE/NPSS SOFE*, Atlantic City NJ, Oct. 2-5, 2001.

M. S. Tillack, J. Pulsifer and K. Sequoia, "UV Laser-Induced Damage to Grazing Incidence Metal Mirrors," *Inertial Fusion Science and Applications 2003*, Monterey CA, Sept. 2003 (pp. 810-814).

K. L. Sequoia, M. S. Tillack, T. Albert, M. Wolford and J. D. Sethian, "Grazing Incidence Metal Mirror Mid-Scale Optics Research Plan," UCSD-ENG-111, May 28, 2004.

W. Kowbel and M. S. Tillack, "Hybrid Al/SiC composite optics for IFE applications," *Fusion Science & Technology* **47** (3), April 2005, 596-600.

M. S. Tillack, J. F. Latkowski, J. E. Pulsifer, K. L. Sequoia and R. P. Abbott, "Grazing-Incidence Metal Mirrors for Laser-IFE," UCSD-CER-05-08, September 2005.

B. Laser propagation physics in IFE chambers

C. V. Bindhu, S. S. Harilal, M. S. Tillack, F. Najmabadi A. C. Gaeris, "Laser Propagation and Energy Absorption by an Argon Spark," *Journal of Applied Physics*, **94** no. 12 (15 Dec. 2003).

C. V. Bindhu, S. S. Harilal, M. S. Tillack, F. Najmabadi, A. C. Gaeris, "Energy Absorption and Propagation in Laser Created Sparks," *Applied Spectroscopy* **58**(6) (June 2004) 719-726.

Y. Tao, M. S. Tillack, S. S. Harilal, K. L. Sequoia, B. O'Shay and F. Najmabadi, "Effect of shockwave-induced density jump on laser plasma interactions in low-pressure ambient air," *J. Phys. D: Applied Physics* **39** (2006) 4027-4030.

C. Aerosol generation and transport in IFE chambers

D. Blair and M. S. Tillack, "Particle Formation and Dynamics in the Laser Ablation Plume," *SPIE Conference on Micromachining and Microfabrication*, October 2001, San Francisco, CA.

B. Christensen and M. S. Tillack, "Survey of mechanisms for liquid droplet ejection from surfaces exposed to rapid pulsed heating," UCSD-ENG-100, January, 2003.

M. S. Tillack, D. Blair and S. S. Harilal, "The effect of ionization on cluster formation in laser ablation plumes," UCSD-ENG-103, August 21, 2003.

A. C. Gaeris, B. Harilal, K. Sequoia and M. S. Tillack, "Aerosol Diagnostics for Liquid-Protected IFE Chambers," UCSD-ENG-104, October 1, 2003.

M. S. Tillack, D. Blair and S. S. Harilal, "The effect of ionization on cluster formation in laser ablation plumes," *Nanotechnology* **15**, issue 3 (January 2004) 390-403.

M. R. Zaghoul and A. R. Raffray, "IFE Liquid Wall Response to the Prompt X-Ray Energy Deposition: Investigation of Physical Processes and Assessment of Ablated Material," *Fusion Science & Technology*, **47** (1), 27-45, January 2005.

D. Charged particle transport and magnetic diversion

S. S. Harilal, C. V. Bindhu, M. S. Tillack, F. Najmabadi and A. C. Gaeris, "Plume Splitting and Sharpening in Laser-produced Aluminum Plasma," *Journal of Physics D: Applied Physics* **35** (2002) 2935-2938.

S. S. Harilal, C. V. Bindhu, M. S. Tillack, F. Najmabadi and A. C. Gaeris, "Internal Structure and Expansion Dynamics of Laser Ablation Plumes into Ambient Gases," *Journal of Applied Physics* **93**, 5 (March 2003) 2380–2388.

M. S. Tillack, S. S. Harilal, F. Najmabadi and J. O'Shay, "Magnetic Confinement of an Expanding Laser-Produced Plasma," *Inertial Fusion Science and Applications 2003*, Monterey CA, Sept. 2003 (pp. 319-322).

S. S. Harilal, M. S. Tillack, B. O'Shay, C. V. Bindhu, F. Najmabadi, "Confinement and dynamics of laser produced plasma expanding across a transverse magnetic field," UCSD-ENG-106, October 24, 2003.

S. S. Harilal, M. S. Tillack, B. O'Shay, C. V. Bindhu, F. Najmabadi, "Confinement and dynamics of laser-produced plasma expanding across a transverse magnetic field," *Phys Rev. E*, **69**, 026413 (2004).

S. S. Harilal and M.S Tillack, "Laser plasma density measurements using interferometry," UCSD-ENG-114, October, 2004.

S. S. Harilal, B. O'Shay, M. S. Tillack, C. V. Bindhu, F. Najmabadi, "Fast photography of a laser generated plasma expanding across a transverse magnetic field," *IEEE Transactions on Plasma Science* **33** (2) April 2005, 474-475.

E. Radiative properties of laser-produced plasma

M.S Tillack, J. O'Shay, E. S. Simpson, C. A. Back and H. A. Scott, "Radiation-hydrodynamic analysis of Ti-doped SiO₂ aerogel exposed to 4-ns laser irradiation," UCSD-CER-05-01, January 10, 2005.

C. A. Back, J. F. Seely, J. L. Weaver, U. Feldman, R. Tommasini, S. G. Glendinning, H.-K. Chung, M. Rosen, R. W. Lee, H. A. Scott, **M. S. Tillack** and J. D. Kilkenny, "Underdense radiation sources: moving towards longer wavelengths," *Inertial Fusion Science and Applications 2005*, Biarritz France, Sept. 2005, p. 1173.

M. S. Tillack, K. L. Sequoia, J. O'Shay, C. A. Back and H. A. Scott, "Optimization of plasma uniformity in laser-irradiated underdense targets," *Inertial Fusion Science and Applications 2005*, Biarritz France, Sept. 2005, p. 985.

K. L. Sequoia, M. S. Tillack and H. A. Scott, "A comparison of Hyades and Cretin for modeling laser absorption in underdense plasmas," UCSD-CER-06-09, December 2006.

F. EUV lithography

S. S. Harilal, Beau O'Shay, Mark S. Tillack and Manoj V. Mathew, "Spectroscopic Characterization of Laser-induced Tin Plasma," *J. Applied Physics* **98**, 013306 (July 2005).

S. S. Harilal, B. O'Shay, M. S. Tillack and Y. Tao, "Spectral control of emissions from Sn-doped targets for EUV lithography," UCSD-CER-05-05, August 2005.

S. S. Harilal, J. O'Shay, M. S. Tillack, Y. Tao, R. Paguio, A. Nikroo and C. A. Back, "Spectral control of emissions from Sn-doped targets for EUV lithography," *J. Phys. D: Applied Physics* **39** (2006) 484-487.

S. S. Harilal, J. O'Shay and M. S. Tillack, "Debris Mitigation in a Laser-Produced Tin Plume Using a Magnetic Field," *J. Applied Physics* **98**, 1 (August 2005).

Y. Tao, M.S. Tillack, S.S. Harilal, B. O'Shay, K. Sequoia and F. Najmabadi, "Comprehensive and reliable diagnostics for the corona of laser-produced plasmas," UCSD-CER-05-06, September 2005.

Y. Tao, M.S. Tillack, S.S. Harilal, B. O'Shay and F. Najmabadi, "Characterizing and optimizing the density profile of double-pulse laser-produced Sn-based plasmas to enhance conversion efficiency and mitigate debris for an EUVL source," UCSD-CER-05-07, September 2005.

M. V. Mathew, S. S. Harilal and M. S. Tillack "Emission characteristics and dynamics of neutral species in a laser-produced tin plasma," *J. Physics D: Applied Physics* **39** (2006) 1-6.

S. S. Harilal, M. S. Tillack, Y. Tao, B. O'Shay, R. Paguio and A. Nikroo, "Extreme ultraviolet spectral purity and magnetic ion debris mitigation with low density tin targets," *Optics Letters* **31** (10) 1549-1551 (May 15, 2006).

S. S. Harilal, Beau O'Shay, Yezheng Tao and Mark S. Tillack, "Ambient gas effects on the dynamics of laser-produced tin plume expansion," *Journal of Applied Physics* **99**, 083303 (2006).

Y. Tao, S. S. Harilal, M. S. Tillack, K. L. Sequoia, B. O'Shay, and F. Najmabadi, "Effect of focal spot size on in-band 13.5 nm extreme ultraviolet emission from laser-produced Sn plasma," *Optics Letters* **31**, 2496 (2006).
(also appears in the Virtual Journal of Ultrafast Science, August 2006).

Y. Tao and, M. S. Tillack, "Mitigation of fast ions from laser-produced Sn plasma for an extreme ultraviolet lithography source," *Appl. Phys. Lett.* **89**, 111502 (2006).
(also appears in the *Virtual Journal of Ultrafast Science*, October 2006)

S. S. Harilal, B. O'Shay, Y. Tao and M. S. Tillack, "Ion debris mitigation from tin plasma using ambient gas, magnetic field and combined effects," *Applied Physics B*, DOI: 10.1007/s00340-006-2532-3, (2006).

B. O'Shay, F. Najmabadi, S. S. Harilal, M. Tillack "Nanosecond spectroscopy of expanding laser-produced tin plasma," The 8th International Conference on Laser Ablation, Banff, Canada, September 11-16, 2005 (to appear in *Journal of Physics: Conference Proceedings*).

Y. Tao, M. S. Tillack, S. S. Harilal, K. L. Sequoia, and F. Najmabadi, "Investigation of the interaction of a laser pulse with a preformed Gaussian Sn plume for an extreme ultraviolet lithography source," *Journal of Applied Physics* (to appear).

G. General publications on IFE

B. G. Logan, W. R. Meier, Ralph W. Moir, M. A. Abdou, P. F. Peterson, G. L. Kulcinski, **M. S. Tillack**, J. F. Latkowski, David Petti, K. R. Schultz, A. Nobile, "Progress and Critical Issues for IFE Blanket and Chamber Research," *Fusion Eng. & Design* **51-52** (2000) p. 1095-1101.

W. Meier, M. Abdou, G. Kulcinski, R. Moir, A. Nobile, P. Peterson, D. Petti, K. Schultz, **M. S. Tillack** and M. Yoda, "Overview of IFE Chamber and Target Technologies R&D in the U.S.," *Proceedings of the 18th IAEA Fusion Energy Conference*, Sorrento Italy, Sept. 2000.

W.R. Meier, D.T. Goodin, A. Nobile, G. Besenbruch, D. Haynes, J. Hoffer, J. Latkowski, J. Maxwell, F. Najmabadi, A. Nikroo, P. Peterson, R. Petzoldt, W. Rickman, J. Sethian, W. Steckle, E. Stephens, **M. Tillack**, A. Ying, and M. Yoda, "Addressing Key Science and Technology Issues for IFE Chambers, Target Fabrication and Target Injection," *19th IAEA Fusion Energy Conference*, Lyon France, Oct. 14-19, 2002. (IAEA-CN-94/FT/1-3Ra).

Rulon Linford, Riccardo Betti, Jill Dahlburg, James Asay, Michael Campbell, Phillip Colella, Jeffrey Freidberg, Jeremy Goodman, David Hammer, Joseph Hoagland, Steve Jardin, John Lindl, Grant Logan, Keith Matzen, Gerald Navratil, Arthur Nobile, John Sethian, John Sheffield, **Mark Tillack**, and Jon Weisheit, "A Review of the U.S. Department of Energy's Inertial Fusion Energy Program," *Journal of Fusion Energy* **22** (2), June 2003.

M. S. Tillack, "IFE Chamber Physics Research Needs: A White Paper," UCSD-ENG-110, March 2004.