Soft X-Ray Laser Interferometry of Colliding Laser-Created Plasmas in Semicylindrical Cavities

Michael A. Purvis, Jonathan Grava, Jorge Filevich, Mario C. Marconi, James Dunn, Stephen J. Moon, Vyacheslav N. Shlyaptsev, Elizabeth Jankowska, and Jorge J. Rocca, *Fellow, IEEE*

***Abstract*—A tabletop capillary discharge soft X-ray laser was used to acquire high-contrast interferograms that map the evolution of dense aluminum plasmas created by the laser irradiation of a 500-μm-diameter semicylindrical cavity with 120-ps optical laser pulses of $\sim 1.1 \times 10^{12} -\ \mathrm{W} \cdot \mathrm{cm}^{-2}$ peak intensity. The measured electron density maps, which were compared with simulations, show that the plasma converges on axis where it collides to form a localized region with density exceeding $1 \times 10^{20}\ \mathrm{cm}^{-3}$.**

***Index Terms*—Colliding plasmas, plasma diagnostics, soft X-ray laser, soft X-ray laser interferometry.**

PLASMAS created by intense laser pulses irradiating solid targets usually expand in directions that are perpendicular to the target surface, along the strong pressure gradients that are generated by the high temperatures and densities near the wall. For concave target geometries, this direction of expansion can force the laser-created plasma to converge into a focal region where it can collide with itself. For example, the laser heating of a semicylindrical cavity (half hohlraum) accelerates plasma toward the axis of the cavity where plasma interactions can range from stagnation to extended interpenetration depending on the degree of collisionality of the plasma [1]. Detailed electron density maps are very useful for understanding the dynamics of these colliding plasmas and for benchmarking plasma simulation codes. However, they are difficult to obtain by using optical laser probes due to the presence of strong density gradients that deflect the probe beam. Soft X-ray laser interferometry is a powerful plasma diagnostic tool that has the ability to access very high densities and large scale length plasmas with a reduced refraction and free-free absorption of the probe beam, allowing for the generation of detailed maps of the electron density in high-density plasmas [2], [3].

Interferograms were obtained by using a Ne-like Ar 46.9-nm tabletop capillary discharge soft X-ray laser probe beam [4] and an amplitude division soft X-ray interferometer [3]. The probe beam was configured to deliver pulses of $\sim$1-ns duration and $\sim$0.15 mJ of energy. The good spatial coherence of this laser assists the generation of interferograms with high fringe visibility. The skewed Mach–Zehnder interferometer uses gold-coated diffraction gratings as beam splitters and grazing incidence gold-coated mirrors to achieve a high throughput of $\sim$6% per arm. The dense colliding plasma was created by focusing 600-mJ pulses of 120-ps duration from a $\lambda = 800 -$ nm Ti: Sapphire laser onto the surface of a semicylindrical target. The laser beam was smoothed by a vacuum spatial filter, and it was shaped into a 310-μm-wide 1.5-mm-FWHM-long line focus by a pair of cylindrical lenses. The targets consisted of 500-μm-diameter semicylindrical cavities machined onto the edge of a 1-mm-thick aluminum slab. The targets were placed along the zero order arm of the interferometer. The plasmas were imaged with 25 times magnification onto a microchannel-plate/CCD detector using Sc/Si multilayer mirrors.

A sequence of interferograms was acquired to map the evolution of the plasma. The interferograms show the early creation of a plasma that expands away from the wall to converge in a small region near the axis of the cavity, where it collides forming a dense plasma focus. The resulting buildup of density at the focus develops as early as 1.5 ns after the peak of the irradiation pulse, with the electron density progressively increasing to exceed $1 \times 10^{20}\ \mathrm{cm}^{-3}$. Fig. 1(a) shows a high-contrast soft X-ray interferogram acquired 4.4 ns after the irradiation pulse. The large number of fringe shifts observed slightly to the right of the axis of the cavity describes the high-density focal region. Fig. 1(b) shows the electron density map constructed from the interferogram.

The single fluid radiation hydrodynamics code HYDRA was used to simulate the 2-D symmetric experiment that was previously described and generate time-dependent 2-D maps of the electron density and other plasma parameters [5]. The code uses an Arbitrary Lagrangian–Eulerian grid. The simulations show that the peak electron density $(1.1 \times 10^{20}\ \mathrm{cm}^{-3})$ and electron temperature ($\sim$50 eV) at the focus occurs $\sim$2.6 ns after the irradiation pulse, in good agreement with the experiments. The laser model included the Gaussian-shaped irradiation pulse, which shows the creation of a hotter plasma at the bottom of the groove. This plasma expands more rapidly and reaches the axis of the cavity first, where it converges, forming the observed high-density plasma focus. The later arrival of additional plasma created by the plasma radiation-induced ablation of the entire target cavity wall causes the electron density at the focus to remain high until $\sim$7 ns after

Manuscript received November 30, 2007. This work was supported by the National Nuclear Security Administration under the Stewardship Science Academic Alliances Program through the U.S. Department of Energy Research Grant DE-FG52-06NA26152.

M. A. Purvis, J. Grava, J. Filevich, M. C. Marconi, and J. J. Rocca are with the NSF ERC for Extreme Ultraviolet Science and Technology and the Department of Electrical and Computer Engineering, Colorado State University, Fort Collins, CO 80523 USA.

J. Dunn and S. J. Moon are with the Lawrence Livermore National Laboratory, Livermore, CA 94551 USA.

V. N. Shlyaptsev is with the Department of Applied Science, University of California Davis-Livermore, Livermore, CA 94551 USA.

E. Jankowska is with the Wroclaw University of Technology, 50-370 Wroclaw, Poland.

Digital Object Identifier 10.1109/TPS.2008.924399

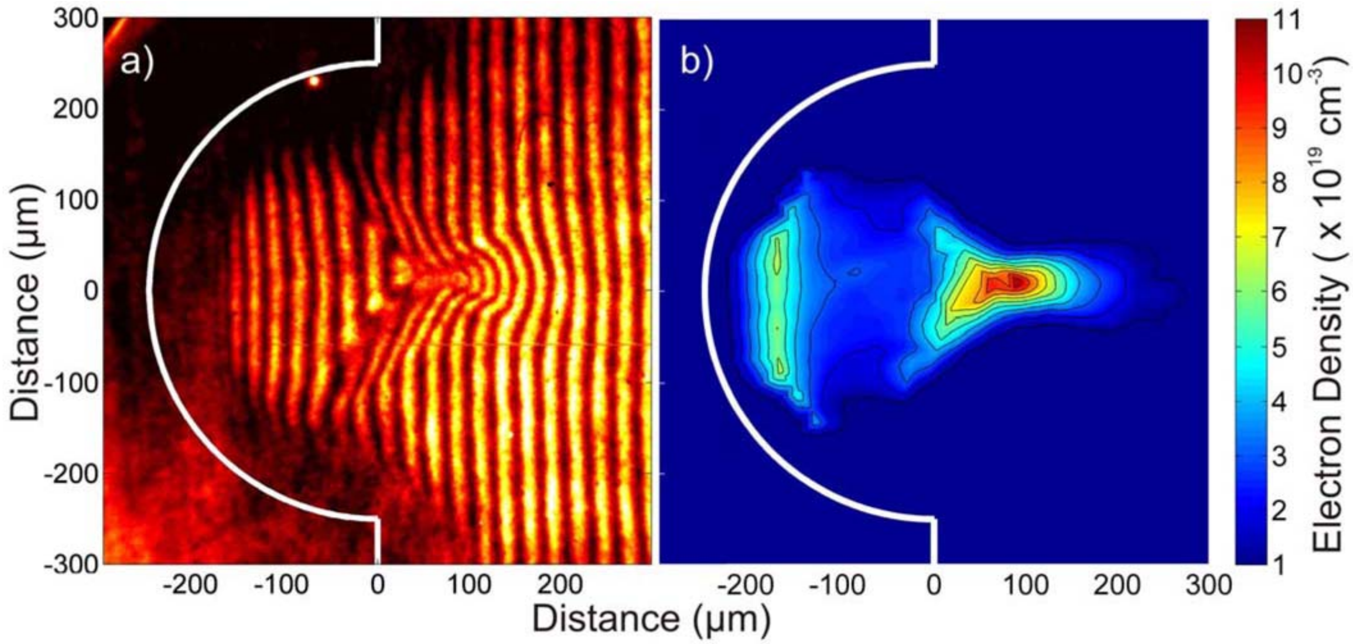

Fig. 1. (a) Soft X-ray interferogram of a plasma created by the laser irradiation of a 500-μm-diameter semicylindrical Al cavity at an intensity of 1.1×10^{12} W $\cdot$ cm^{-2} with a 120-ps-duration laser pulse and (b) the resulting electron density map. The interferogram depicts the plasma at 4.4 ns after the peak of the laser irradiation pulse.

the arrival of the irradiation pulse. Subsequently, the density is observed to relax as the plasma expands and cools. The ion-ion mean free path is computed to be nearly two orders of magnitude smaller than the plasma focus size, an indication that the plasma is highly collisional. The good agreement between the experimental results and the simulations with the fluid code HYDRA, which cannot model interpenetration, indicates that the plasma is highly collisional and stagnates on axis without significant interpenetration. More information on the dynamics can be found in a recent publication [6].

In conclusion, soft X-ray laser interferometry was used to study dense colliding aluminum plasmas formed by the optical irradiation of a semicylindrical cavity. The measurements reveal that plasma accumulation near the axis of the cavity creates a highly collisional plasma focus with a density that exceeds 1×10^{20} cm^{-3}. The measurements are in good agreement with hydrodynamic simulations. These results further demonstrate that soft X-ray interferometry is a powerful tool for probing dense plasmas.

ACKNOWLEDGMENT

The authors would like to thank the NSF ERC Center for Extreme Ultraviolet Science and Technology for allowing the use of their facilities under Grant EEC-0310717. Part of this work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

REFERENCES

[1] M. E. Jones, D. Winske, S. R. Goldman, R. A. Kopp, V. G. Rogatchev, S. A. Bel'kov, P. D. Gasparyan, G. V. Dolgoleva, N. V. Zhidkov, N. V. Ivanov, Y. K. Kochubej, G. F. Nasyrov, V. A. Pavlovskii, V. V. Smirnov, and Y. A. Romanov, "Modeling ion interpenetration, stagnation, and thermalization in colliding plasmas," *Phys. Plasmas*, vol. 3, no. 3, p. 1096, Mar. 1996.

[2] L. B. Da Silva, T. W. Barbee, Jr., R. Cauble, P. Celliers, D. Ciarlo, S. Libby, R. A. London, D. Matthews, S. Mrowka, J. C. Moreno, D. Ress, J. E. Trebes, A. S. Wan, and F. Weber, "Electron density measurements of high density plasmas using soft x-ray laser interferometry," *Phys. Rev. Lett.*, vol. 74, no. 20, pp. 3991–3994, May 1995.

[3] J. Filevich, K. Kanizay, M. C. Marconi, J. L. A. Chilla, and J. J. Rocca, "Dense plasma diagnostics with an amplitude-division soft-x-ray laser interferometer based on diffraction gratings," *Opt. Lett.*, vol. 25, no. 5, pp. 356–358, Mar. 2000.

[4] B. R. Benware, C. D. Macchietto, J. L. A. Chilla, and J. J. Rocca, "Demonstration of a high average power tabletop soft x-ray laser," *Phys. Rev. Lett.*, vol. 81, no. 26, pp. 5804–5807, Dec. 1998.

[5] M. M. Marinak, S. W. Haan, T. R. Dittrich, R. E. Tipton, and G. B. Zimmerman, "A comparison of three-dimensional multimode hydrodynamic instabilitygrowth on various National Ignition Facility capsule designs with HYDRA simulations," *Phys. Plasmas*, vol. 5, no. 4, pp. 1125–1132, Apr. 1998.

[6] M. Purvis, J. Grava, J. Filevich, M. C. Marconi, J. Dunn, S. J. Moon, V. N. Shlyaptsev, E. Jankowska, and J. J. Rocca, "Dynamics of converging laser-created plasmas in semicylindrical cavities studied using soft x-ray laser interferometry," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 76, no. 4, p. 046 402, Oct. 2007.