Supersonic heat wave propagation in laser-produced underdense plasma for efficient x-ray generation

Minoru Tanabe, Hiroaki Nishimura, Shinsuke Fujioka, Keiji Nagai, Atsushi Iwamae¹, Naofumi Ohnishi², Kevin B. Fournier³, Frederic Girard⁴, Michel Primout⁴, Bruno Villette⁴, Mike Tobin⁵, and Kunioki Mima

Institute of Laser Engineering, Osaka University, Suita, Osaka 565-0871, Japan
¹Department of Mechanical Engineering and Science, Kyoto University, Kyoto 606-8501, Japan
²Department of Aerospace Engineering, Tohoku University 6-6-01 Aramaki-Aza-Aoba, Aoba-ku, Sendai 980-8579, Japan
³Lawrence Livermore National Laboratory, P.O. Box 808, L-41, Livermore, California 94550, USA
⁴Commissariat a l’Energie Atomique, DAM-Ile-de-France, BP12, 91680 Bruyeres-le-chatel, France
E-mail: mtanabe@ile.osaka-u.ac.jp

Abstract. We have observed supersonic heat wave propagation in a low-density aerogel target (ρ ∼ 3.2 mg/cm³) irradiated at the intensity of 4 × 10¹⁴ W/cm². The heat wave propagation was measured with a time-resolved x-ray imaging diagnostics, and the results were compared with simulations made with the two-dimensional radiation-hydrodynamic code, RAICHO. Propagation velocity of the ionization front very slightly decreased as the wave propagates into the target. The reason of decrease is due to increase of laser absorption region as the front propagates and interplay of hydrodynamic motion and reflection of laser propagation in the target. These features are well reproduced with the simulation.

1. Introduction
Laser driven multi-keV x-ray sources are powerful tools for radiographic techniques used in such as experiment for laboratory astrophysics, high-energy-density physics, and inertial confinement fusion (ICF) research [1]. These experiments require high conversion efficiency (CE), high photon energies, and uniformity of x-ray sources. Multi-keV x-ray is typically radiated from high temperature region that is highly ionized. In a solid target, laser energy absorbed at the critical density is transported via electron thermal conduction into the dense region. The x-ray emission region for the solid target is small due to steep gradients in density and temperature of the plasma. For underdense targets such as gasses, doped aerogel, or doped foam, whose electron densities are lower than the critical density for drive laser wavelength, laser energy is directly absorbed at the x-ray emission region via inverse bremsstrahlung, thus the target is heated volumetrically and supersonically [2,3]. The volume of multi-keV x-ray emission region may be larger than that in the solid target. The volumetric and supersonic heating without hydrodynamic energy losses is the key mechanism for efficient multi-keV x-ray generation [4,5,6]. Understanding the detailed physics associated with heat-wave propagation in
underdense plasmas is of great importance for clarifying the optimum conditions for multi-keV x-ray generation.

Several investigations were previously carried out to measure the heat-wave propagation in the different conditions [2,3,7]. This paper presents measurement of heat wave propagation in the underdense plasma at relatively low intensity of $4 \times 10^{14}$ W/cm$^2$. The experimental results are compared to simulations with two-dimensional radiation-hydrodynamic code RAICHO [8] in order to understand energy transport, hydrodynamic motion in the target, and laser propagation occurring in the underdense target.

2. Experimental set-up
The target used in this experiment was a low-density silica aerogel with a doping of 3% Ti by atomic number density [5]. The aerogel target had total electron density of $9 \times 10^{20}$ cm$^{-3}$, corresponding to 0.1 times the critical density for 351 nm laser wavelength when the target is fully ionized. The aerogel was packed in a 75 µm thick Be cylinder of 1 mm in diameter and 1.94 mm in length.

The experiment was performed on the GXII HIPER laser facility at Institute Laser Engineering, Osaka University. Wavelength and pulse are 351 nm and 2.5 ns bell-shape, respectively. The cone half angle of the laser beam is 9.4°, which corresponds to F/3. All nine beams of the GXII were focused at 1130 µm in front of the target surface. The incident laser energy was approximately 100 J/beam. With these conditions, the laser intensity on the target surface was $4 \times 10^{14}$ W/cm$^2$.

To observe the heat wave propagation in the target, an x-ray streak camera was installed perpendicular to the cylinder axis. A 20 µm-diameter pinhole was used as an imager device, and the magnification was 8.7. A 100 µm-thick Be foil was set in front of the pinhole to shield from debris and a 5 µm-thick titanium foil was used to select the observable x-ray energy range (≈ 4.9 keV). A 700 µm width streak slit was aligned in parallel to the cylinder axis in order to observe only the region close to the axis. The time resolution was 110 ps and the space resolution was 23 µm for the Ti-Heo line.

3. Results and discussions

![Figure 1](image_url)

**Figure 1.** (a) Time- and space-resolved observed x-ray image. (b) Time- and space- resolved electron temperature map calculated with RAICHO. (c) Experimental laser pulse shape used in the simulation. In both (a) and (b), the laser was incident on the target from the left hand side.

Figure 1(a) shows a streaked image of Ti K-shell x-ray emission region. The emitted x-ray is dominated by the Ti-Heo line. We used RAICHO [8], a two-dimensional, Eulerian radiation-hydrodynamics code to simulate the experiment. The simulation included experimental laser
energy, laser spot, and pulse shape. Two-dimensional ray-tracing techniques were used to track the laser propagation in the target. Laser energy was deposited by inverse bremsstrahlung. The thermal electron conduction was treated with the classical Spitzer-Härm formula with the flux limiter \( f = 0.1 \). Figure 1(b) shows temporal evolution of spatial electron temperature profile along the center of cylinder axis as calculated with RAICHO. The time origin in Fig. 1(b) is the same as that in Fig. 1(c). The time in Fig. 1(a) image was adjusted to coincide with the simulation result (see Fig 2).

In our experimental analysis, the position of the ionization front was defined as \( 1/e \) of the peak x-ray intensity. The initial velocity of the front was approximately \( 2 \times 10^8 \) cm/s, which is a Mach number of 10 for the electron temperature of 1 keV. Figure 2 shows comparison of trajectory of the ionization front observed in the experiment and the calculated electron temperature front of 1 keV at time until the ionization front reaches the other target side. The comparison shows a good agreement. The wave propagation was very slightly decelerated as the ionization front propagates into the target. The primary reason is the increase of laser-energy absorption as the front propagates. However the ionization-front propagation velocity is affected by a complicated interplay of laser propagation with hydrodynamic motion, mostly from the cylinder wall, that occurs as follows.

![Comparison of trajectories of the ionization front.](image)

**Figure 2.** Comparison of trajectories of the ionization front. The square dots represent the experimental results, and the line shows the trajectory of the calculated electron temperature front of 1 keV.

At 2.3 ns, a part of the laser pulse reflected from the cylinder wall is focused on the central axis of the cylinder. In Fig. 3, time- and space-resolved ray-tracing and heating rates calculated with RAICHO are shown at 2.3 ns, 2.5 ns, and 2.6 ns. As time advances, high temperature region moves backward toward the laser incident side. These results suggest that the laser-reflection point moves backward as the cylindrical wall of the target expands inward and the normal direction to the surface changes with respect to the laser-propagation axis.

![Time- and space-resolved laser ray-tracing and heating rate calculated with RAICHO](image)

**Figure 3.** Time- and space-resolved laser ray-tracing and heating rate calculated with RAICHO: (a) 2.3 ns, (b) 2.5 ns, and (c) 2.6 ns. For all images, the upper and lower images respectively show ray-tracing and heating rate.
Figure 4 shows the time- and space-resolved electron temperature and electron density profiles calculated with RAICHO at 2.3 ns, 2.6 ns, and 2.9 ns. At 2.9 ns, the plasmas expanding from the cylinder wall collide and stagnate at the center of the cylinder near the irradiated face of the target. At that time, the electron temperature increases at the entrance of the cylinder (see Fig. 1(b)). In comparison with Figs. 1(a) and (b), the streaked image and calculated on-axis electron temperature history in Figs. 1(a) and 1(b) also indicates these features are due to laser focusing in the target and collision of the expanding plasmas.

![Figure 4](image)

**Figure 4.** Time- and space-resolved electron temperature and electron density profile calculated with RAICHO: (a) 2.3 ns, (b) 2.6 ns, and (c) 2.9 ns. For all images, the upper and lower images respectively show electron temperature and electron density.

4. Conclusion

Characteristics of heat-wave propagation and relevant phenomena occurring in a low-density Ti-doped aerogel target at $4 \times 10^{14}$ W/cm² were presented. The dynamics of supersonic heating in the aerogel were investigated on the basis of RAICHO simulations. An overall agreement was obtained in the comparison. We conclude that the underdense targets are suitable platform to investigate the laser energy absorption and deposition, heat transport, and hydrodynamic motion. These processed are of great importance for benchmarking radiation-hydrodynamic code for highly efficient x-ray sources.

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References

[1] Lindl J, Amedt P, Berger R L, Glendinning S G, Glenser S H, Haan S W, Kauffman R L, Landen O L, and Suter L J 2004 *Phys. Plasmas* **11** 339.

[2] Koch J A, Estabrook K G, Bauer J D, Back C A, Klein L, Rubenchik A M, Hsieh E J, Cook R C, MacGowan B J, Moody H D, Moreno J C, Kalantar D, and Lee R W 1995 *Phys. Plasmas* **2** 3820.

[3] Constantin C, Back C A, Fournier K B, Gregori G, Landen O L, and Miller M C 2005 *Phys. Plasmas* **12** 063104.

[4] Back C A, Grun J, Decker C, Suter L J, Davis J, Landen O L, Wallace R, Hsing W W, Laming J M, Feldman U, Miller M C, and Wuest C 2001 *Phys. Rev. Lett.* **87** 275003.

[5] Fournier K B, Constantin C, Poco J, Miller M C, Back C A, Suter L J, Satcher J, Davis J, and Grun J 2004 *Phys. Rev. Lett.* **92** 165005.

[6] Girard F, Jadaud J P, Naudy M, Villette B, Babonneau D, Primout M, Miller M C, Kauffman R L, Suter L J, Grum J, and Davis J 2005 *Phys. Plasmas* **12** 092705.

[7] Ditmire T, Gunbrell E T, Smith R A, Mountford L, and Hutchinson M H R 1996 *Phys. Rev. Lett.* **77** 498.

[8] Ohnishi N, Nishikino M, and Sasaki A 2006 *J. Phys. IV France* **133** 1193.