Laser and Particle Beams (2006), *24*, 495–501. Printed in the USA.

DOI: 10.1017/S0263034606060654

Two-photon group radiation transfer study in low-density foam cylinder

YAN XU,[1] SHAOENG JIANG,[2] DONGXIAN LAI,[1] WENBING PEI,[1] YONGKUN DING,[2] TIEQIANG CHANG,[1] KE LAN,[1] SHUANGGUI LI,[1] AND TINGGUI FENG[1]
[1]Institute of applied physics and computational mathematics, Beijing, China
[2]Research Center of Laser Fusion, CAEP, Mianyang, China

(Received 3 June 2006; Accepted 10 July 2006)

Abstract

Radiation transfer in low-density foam is influenced by the external radiation field which impacts on the foam when the size of plasma created in laboratory is not large to be opatical thick. The radiation transfers of different photon groups are sensitive probes of the conditions of the medium through which they propagate. The temporal behavior of photon groups to which the plasma is optical thin is quite different from that of photon groups to which the plasma is optical thick. The breakout times of different photon groups through the foam are distinguishable different in experiment when we measures them at the end of foam. The multi-group supersonic radiation transfer behavior in low-density foam is studied both by multi-group transfer numerical simulation and experiments. Two characteristic photon groups are chosen to do experimental research on the multi-group transfer behavior in low-density CH foam. A time-resolved chromatic streaked X-ray spectrometer measure the breakout of the two photon group from the far end of the foam cylinder. The distinguishable transfer time delay between two groups is observed.

Keywords: Low-density foam cylinder; Supersonic radiation transfer; Transfer time delay

1. INTRODUCTION

Radiation transfer is very important in many fields such as astrophysics and schemes to produce fusion energy in the laboratory (Feugeas, 2004; Minguez *et al.*, 2005). Due to the complex interaction of radiation with matter, the solution to the radiation transfer equation is particularly difficult (Pomraning, 1966; Mihalas & Mihalas, 1984; Castor, 2004) when an external radiation field significantly impacts the energy flux. Various approximations have been made to reduce the complexity. The diffusion approximation is one of the important approximation treatments of radiation transport. Extensive analytic analysis is given to describe diffusive supersonic radiation transfer in medium (Marshak, 1958; Zel'dovich & Raizer, 1966). The accuracy of those approximations needs the experiments to check them. High power laser facilities have enabled experimental investigations of the radiation transfer in medium (Jungwirth, 2005; Danson *et al.*, 2005). Radiation transfer has been investigated in the laboratory both in optically thin plasma (Massen *et al.*, 1994; Afshar-rad *et al.*, 1994; Hoarty *et al.*, 1999) and in optically thick plasma (Back *et al.*, 2000*a*, 2000*b*). The size of the plasma is determined by the energy needed to create it; therefore, plasma that is created in the laboratory in most cases is optical thin, one due to relatively low laser energy. Since radiation transfer is a sensitive probe of the conditions of the medium through which it propagates, the research of radiation transfer in average optical thin plasma will benefit us in both physics and diagnosis.

When the optical depth of the plasma created is limited to $\sim$1 mean free path, the phenomena must be described by multi-group transfer model due to the breakdown of diffusion approximation, especially when radiation propagates in low-density low Z foam (Apruzese *et al.*, 2002; Canaud *et al.*, 2004; Philippe *et al.*, 2004; Limpouch *et al.*, 2005).The multi-group transfer description is crucial to predict the non-local high temperature radiation's transfer in medium whose property is determined by local material temperature and density. When the medium is primarily composed of low and medium atomic number elements, the medium's absorption of radiation is often dominated by absorption from well-separated core of spectral lines. This is especially true in CH foam when most of the ions are in the H- or He-like K shell or certain L-shell ionization stages with relatively simple spectra. While many of these lines are

Address correspondence and reprint requests to: Yan Xu, Institute of applied physics and computational mathematics, Beijing 100088, China. E-Mail: xu_yan@mail.iapcm.ac.cn

optically thick, there is absorption window between such core of spectral lines from L shell ionization and that from K shell ionization of carbon in CH plasma. The radiation in the absorption window penetrates into medium deeper and influences the formation of temperature profile or shape of ionization front, while the photons in optically thick frequency range are absorbed and re-emitted many times in all direction before they reach the ionization front. In this paper, we illustrate investigation of multi-group transport by measuring the transfer time of two characteristic photon groups through low-density CH foam.

Section 2 presents the analysis of radiation interaction with CH foam. The influence of frequency dependent opacity on shape of ionization front is also present. Two characteristic photon groups, one located in absorption window while the other located in core of strong lines from K shell ionization, are found to have different transfer time through the CH foam. To verify it, those two photon groups are chosen to do experimental research on the multi-group transfer in low-density CH foam. Section 3 describes the experimental research on two photon groups transfer in CH foam. Experiments have been done in Shengguang II laser facility in China. The laser beams heat a gold cylinder hohlraum to create intense X-ray radiation of about 160 eV at its peak. The radiation field heat the foam filled in another gold cylinder that is put on the side of hohlraum. The propagations of the two photon groups are measured by a time-resolved chromatic streaked X-ray spectrometer when they break out in the far end. Repetitious X-ray images show obvious transfer time delay of the two photon groups. Section 4 gives the comparison of simulation results with experimental results. The last section concludes with the experimental observation and numerical simulation.

2. NUMERICAL SIMULATION OF RADIATION TRANSFER IN CH FOAM CYLINDER

When radiation and a medium reach local thermodynamic equilibrium (LTE), the radiation transport equation can be written as

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \vec{\Omega}\cdot\nabla I_\nu = \mu'(B_\nu - I_\nu). \qquad (1)$$

The scattering term is much smaller than the other terms. Here I_ν is the specific intensity at frequency ν, B_ν is the Planck function at local temperature, and μ' is the absorption coefficient. The net energy loss per unite time per volume is

$$q = \int d\nu \int \mu'(B_\nu - I_\nu)\, d\Omega = \int q_\nu\, d\nu. \qquad (2)$$

Here, $-q_\nu$ is the energy that radiation exchanges with the medium at frequency ν.

When radiation energy is absorbed by the medium, the state of the medium will change. The energy equation for the medium is

$$\frac{\partial}{\partial t}\left(\rho\varepsilon + \frac{\rho u^2}{2}\right) + \nabla\cdot\left[\rho\vec{u}\left(\varepsilon + \frac{p}{\rho} + \frac{u^2}{2}\right)\right] = -q, \qquad (3)$$

when $-q_\nu > 0$, the radiation of the frequency is absorbed by the medium and the medium is then heated, while $-q_\nu < 0$, the radiation of the frequency is remitted.

The radiation transfer in CH foam of density 0.05 g/cm^3, filled in a gold cylinder of 0.6 mm diameter and 0.4 mm length is simulated using a two-dimensional multi-group transport code LARED-R-1(Lan *et al.*, 2005). Different photon groups (200, 40, 20 groups and 1 group) and different Sn (Discrete Ordinate) number (S4, S6, and S8) are used to study their influence on plasma state inside the cylinder. It has been found that for photon groups larger than 20 and S4, the calculated plasma states vary very little. The existence of a gold cylinder makes the simulation a two-dimensional one, but due to the large diameter, and short length of the gold cylinder, its influence on radiation transport in the center of the foam cylinder is greatly reduced. One-dimensional multi-group transport code RDMG (Feng *et al.*, 1999) is also used to simulate the case to get a quick physical insight. The ionization front can sustain supersonic transport in CH foam for many hundreds of picoseconds.

The association of energy deposition profile with plasma temperature profile, and the corresponding absorption coefficient spectra are shown in Figure 1, given by 200-group simulation. Figure 1a shows the distribution of the energy deposition in matter $-q_\nu$, along the cylinder axis at 0.8 ns after the radiation turns on. Figure 1b shows the corresponding calculated plasma temperature profile at the cylinder center, along the cylinder axis at time 0.8 ns, while Figure 1c shows the detailed opacity of CH plasma at three plasma states, density 0.05 g/cm^3, and temperature 17 eV, 60 eV, 112 eV, in the cylinder. There is a window of CH opacity spectra in the frequency range around 210 eV as in Figure 1c. The photons that are located in the window penetrate into the cold medium deeper, deposit their energies there, and preheat the medium, just as shown in Figure 1a; there is a large energy deposition of photon group 170 eV–300 eV around the ionization front. There is a core of strong lines in the frequency range around 420 eV. The photons that are located in the region are absorbed and reemitted many times before they reach the ionization front.

Figure 2 shows the association of energy deposition profiles of 180–221 eV and 350–450 eV photon groups with the corresponding plasma temperature profile at 0.9 ns. The photon group of 180–221 eV contributes to the foreland of the ionization front. The external radiation of the frequency range passes through the heat material and deposits its energy mainly at the foreland of the ionization front. While the external radiation of photon group 350–450 eV is absorbed

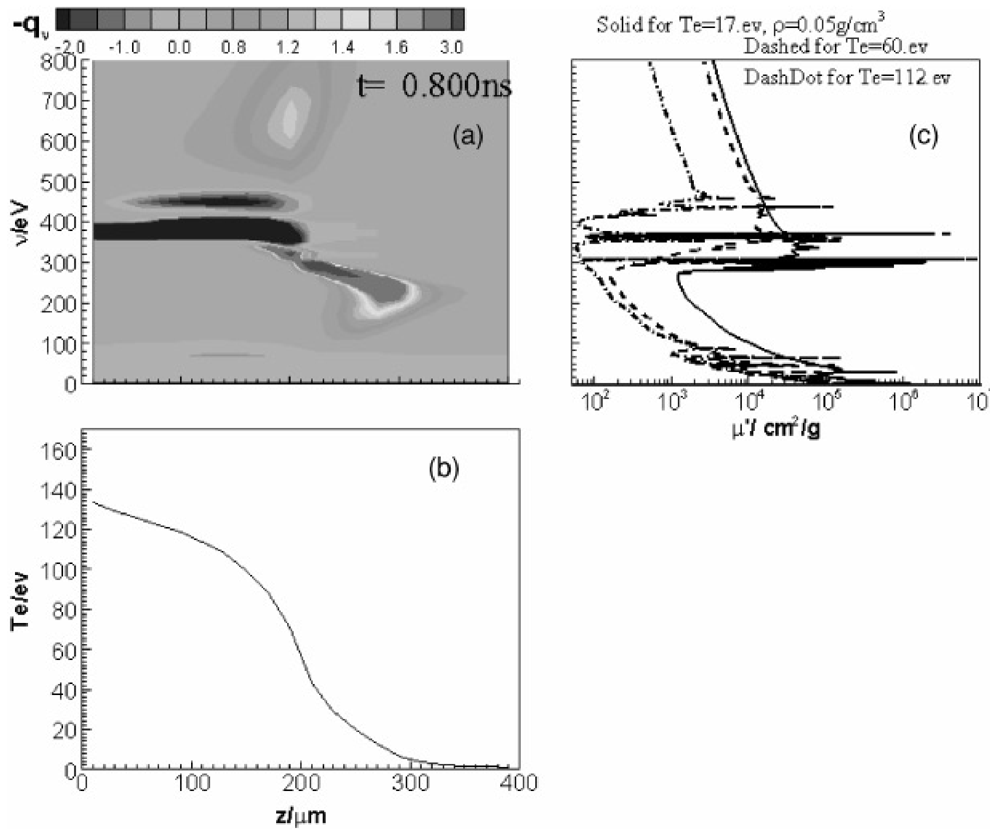

Fig. 1. (**a**) The calculated spectra profile of radiation energy absorbed by medium along cylinder axis at $t = 0.8$ ns. The abscissa is location along cylinder axis. (**b**) The calculated plasma temperature profile along cylinder axis at $t = 0.8$ ns. (**c**) The detailed opacity of CH foam at three plasma temperature 17, 60, 112 eV, and density 0.05 g/cm^3 provided by Prof. Yang Jianmin (private communication).

just near the edge of the plasma, gradually the absorption and reemission reach equilibrium, only in the region of high gradient of the ionization front, where the property of the medium changes, does the radiation energy deposit itself. It contributes to the main part of the ionization front. The medium's reemission plays an important role in the profile of the ionization front. The deposited energies profile from photons of all frequency at 0.9 ns is shown in Figure 3.

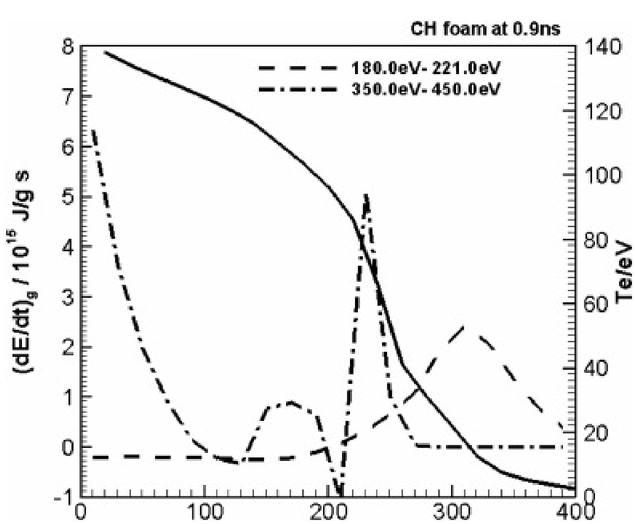

Fig. 2. The association of the calculated energy deposition profile of 180–221 eV (dashed line) and 350–450 eV (dash-dot line) photon group with corresponding plasma temperature profile at 0.9 ns.

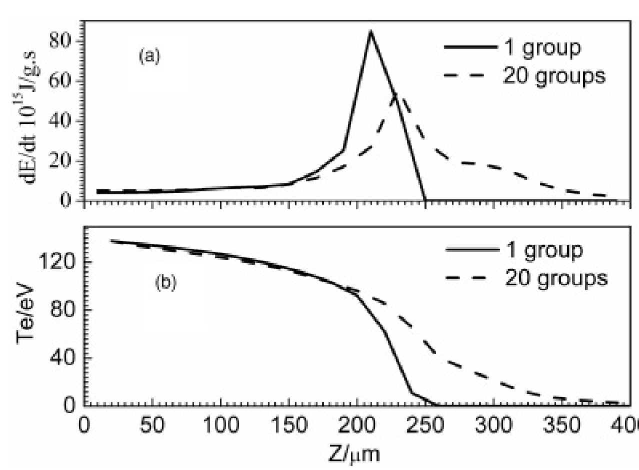

Fig. 3. (**a**) Comparison of energy deposition profile of 20 group simulation (dashed line) with that of 1-group simulation (solid line). (**b**) Comparison of corresponding plasma temperature profile of 20 group simulation (dashed line) with that of 1-group simulation (solid line) at 0.9 ns.

https://doi.org/10.1017/S0263034606060654 Published online by Cambridge University Press

Figure 3 shows the comparison of 1-group transfer (gray = approximation) simulation with 20-groups transfer simulation on both the energy deposition and the plasma temperature profile. The energy deposition profile of 20-groups mode has a wide spatial distribution, while that of the 1-group mode has a sharp one. So are the profiles of the ionization front. The profile of the ionization front in 1-group simulation is relatively steep, while that in 20-groups simulation has a preheat part ahead.

Since photons have different penetrating depth, it is obvious that the transfer times, which they escape the foam at the far end, are different. The heated CH plasma is optically thin to photon group 210 eV with bandwidth 40 eV, and is optically thick to 420 eV with bandwidth 100 eV; therefore these two photon groups are chosen to show the multi-group transport behavior in foam. Figure 4 shows the calculated fluxes of 210 eV and 420 eV that pass through the foam versus time, when a CH foam cylinder with diameter 0.6 mm and length 0.3 mm is heated by radiation with peak radiation temperature 160 eV. There is a distinguishable time delay of their breaking through the far end of the foam. This time delay can be measured in laboratory.

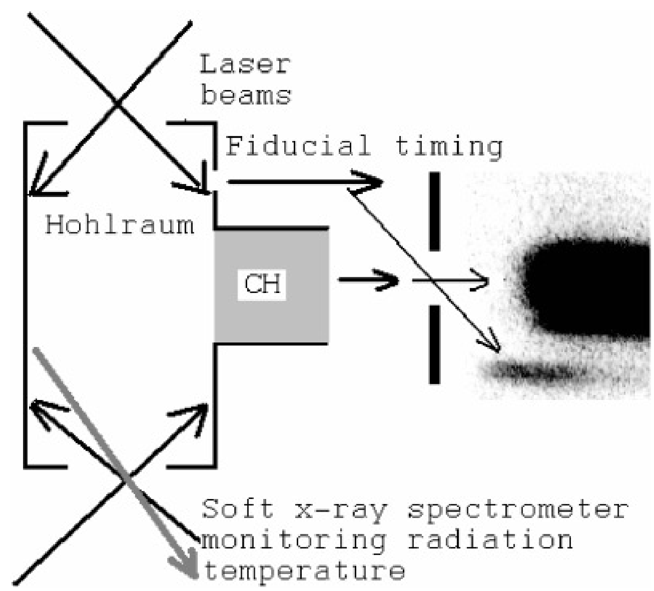

Fig. 5. A schematic of target and imaging geometry to measure transport time and a typical image of 210 eV photon group recorded by streaked X-ray spectrometer.

3. EXPERIMENT TO MEASURE TWO PHOTON GROUP TRANSFER IN CH FOAM

The experiments are carried out in the Shengguang II Nd-glass-laser facility at the High Power Laser Laboratory, Shanghai, China. The Shengguang II laser facility has eight 0.35 μm laser beams with a total energy of 2 kJ and pulse duration of 1 ns. The schematic of the experiment is shown in Figure 5. Eight laser beams heats a gold cylinder cavity (hohlraum) that has a 0.8 mm diameter and 1.7 mm length to produce the drive radiation. All incoming beams have a single cone at an angle of 45° relative to the hohlraum axis. The maximum laser intensity at the wall is about 3×10^{14} W/cm^2.

The temporal behavior of the radiation produced by laser heating the hohlraum is monitored by soft X-ray spectrometers (SXS), from the laser entrance hole (LEH) at angle 30° relative to the hohlraum axis. An oscillograph recorded the laser pulse shape. Figure 6 shows the temporal behavior of the radiation temperature and the laser pulse shape. Their origins of time are not co-related, although they are in the same figure. The SXS were calibrated on the Beijing Synchronization Radiation Facility (BSRF). The SXS has seven energy channels that can measure energy range of 50–1500 eV. The error in the radiation temperature measurement is ± 8%.

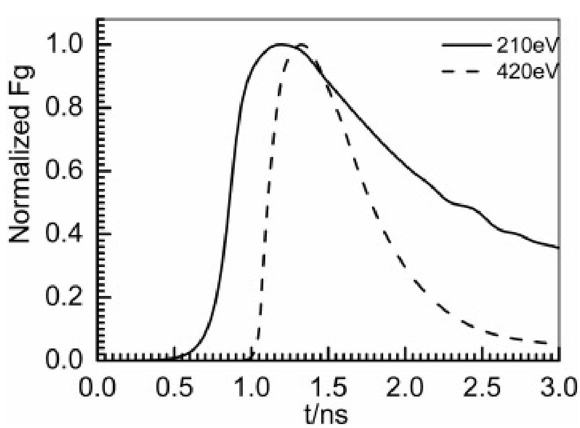

Fig. 4. The calculated fluxes versus time at foam center for two photon groups, 210 eV (solid line) and 420 eV (dashed line) when a CH foam cylinder with diameter 0.6 mm and length 0.3 mm is heated by radiation with peak radiation temperature 160 eV.

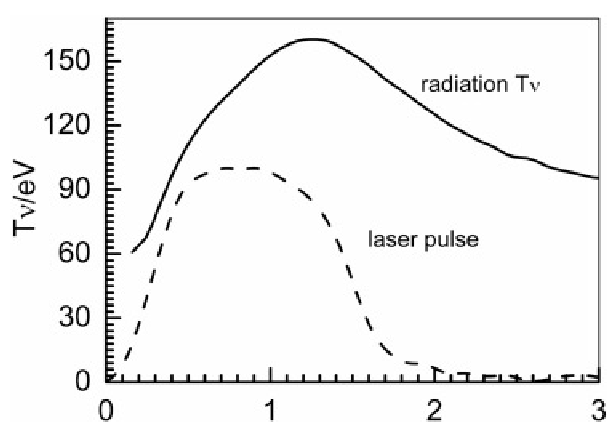

Fig. 6. The measured temporal behavior (solid line) of drive temperature and normalized laser pulse shape (dashed line) are shown.

https://doi.org/10.1017/S0263034606060654 Published online by Cambridge University Press

The radiation will heat the low-density CH foam that is in a gold cylinder, and is put on the side of the hohlraum as shown in Figure 5. The CH foam density is 0.05 g/cm^3. The CH foam cylinder is 0.6 mm in diameter with two different lengths: 0.3 mm and 0.4 mm. A chromatic streaked X-ray spectrometer that consists of imaging pinhole with 10 μm's diameter and transmission grating with 100 μm width, and an X-ray streak camera (XSC) views the foam face-on. The chromatic streaked X-ray spectrometer measures the temporal behavior of flux of the chosen soft X-ray photon group reaching its cathode slit. Another small hole is opened on the side of the hohlraum as a reference hole to monitor the temporal evolution of the drive radiation, also with the chromatic streaked X-ray spectrometer on the same image. This provides fiducially timing of the beginning of radiation. Experiments have been done with different diameter hole on the hohlraum to see whether a smaller hole can record the temporal behavior of radiation. For each size of foam (within manufacture error), several shots have been done. Figure 7 shows a typical image of those experiments. It shows that a small hole with a diameter of 0.15 mm can monitor the radiation from big hole with 0.6 mm diameter in which the CH foam cylinder will be put. Both the flux from the fiducially timing hole and the break through on the far end of the foam are imaged with an X-ray streak camera on the same shot. The temporal resolution of the X-ray streak camera is 8.7 ps/pixel. The measured time delay between the flux from the fiducially timing hole and the flux from the far end of the foam is the transfer time of the photon groups with limited bandwidth through the foam.

Experiments have been done to measure the transfer time of 210 eV photon group with bandwidth 40 eV and 420 eV, photon group with bandwidth 100 eV through CH foam. Figure 8 shows typical images of 210 eV and 420 eV photon group break through CH foam cylinder with 0.3 mm and 0.4 mm lengths. There are two strips in the X-ray streak camera images. The thick strip recorded the flux that broke through the far end of the foam, while the thin strip recorded the driving radiation flux of the corresponding photon group. Using the fiducially timing as the beginning of radiation, the measured fluxes of 210 eV photon group breaking through 0.3 mm and 0.4 mm CH foam are compared as shown in Figure 8d. Figure 8e shows the measured fluxes of 210 eV and 420 eV photon group breaking through 0.3 mm CH foam. Figure 8e shows that after transferring through the foam, the radiation of 420 eV photon group has thinner pulse width than that of 210 eV. This is because the CH foam of the length is optical thick to 420 eV photon group. Only when the far end of foam is heated up does the reemission of the 420 eV photon group come out from the foam. Therefore, it has thinner pulse width. There is a distinguishable time delay for photon group of 210 eV and 420 eV to transfer through a CH foam cylinder with the same length. The multi-group transport behavior is measured. Measurements after the laser pulse is off are often complicated by plasma filling and do not provide definitive quantitative data, so is

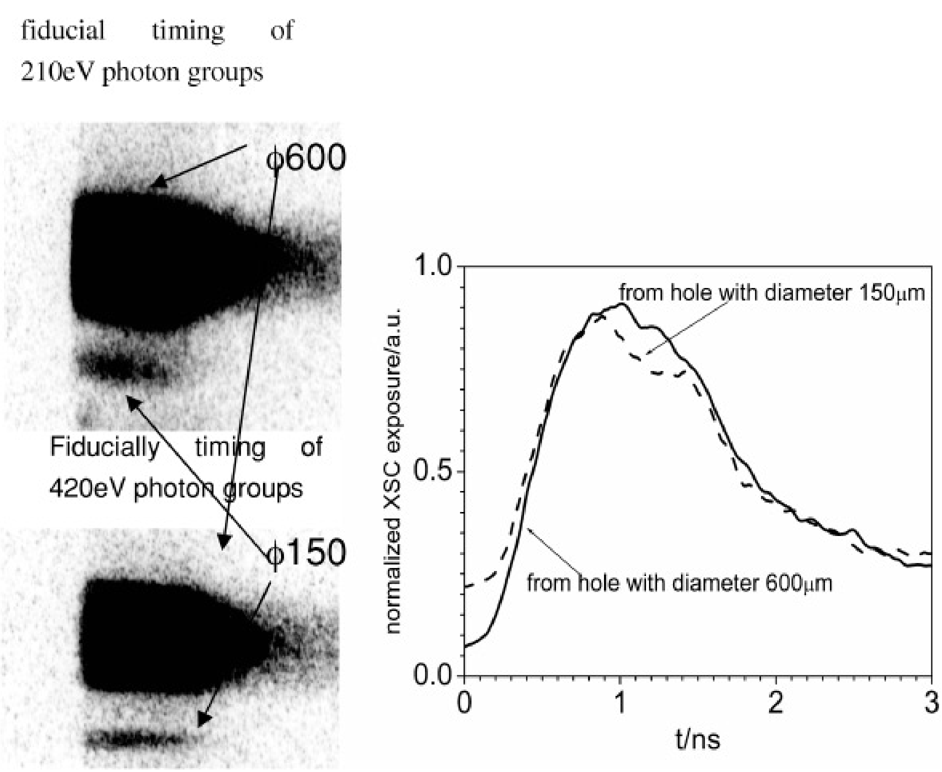

Fig. 7. The X-ray images of two photon groups, 210 eV (upper) and 420 eV (lower) from two holes, one with diameter 150 μm, another with diameter 600 μm on which the foam will be put. The temporal intensity line outs of the 210 eV photon group data are shown in right plot.

https://doi.org/10.1017/S0263034606060654 Published online by Cambridge University Press

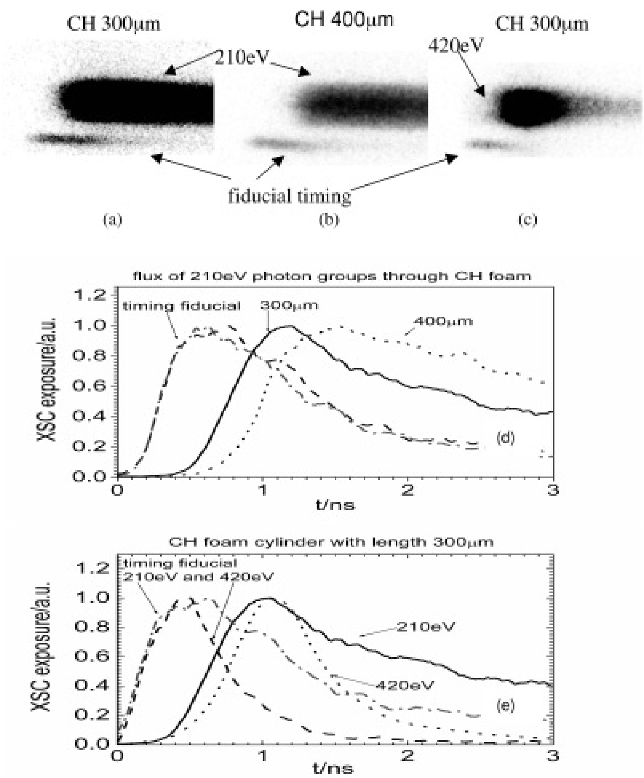

Fig. 8. The X-ray images of CH data which recorded the fluxes of 210 eV photon groups that break through the far end of CH foam cylinder with length (**a**) 300 μm and (**b**) 400 μm, and (**c**) the fluxes of 420 eV photon groups that break through the far end of CH foam cylinder with length 300g μm. The thin strips on the images are emissions directly from the fiducial timing hole to provide beginning time of radiation. (**d**) Comparison data of 210 eV photon group break through 300 μm length CH foam with that break through 400 μm. (e) Comparison data of 210 eV photon group with that of 420 eV photon group when they break through CH foam with 300 μm length.

the data for 420 eV photon group passing through 0.4 mm CH foam.

4. COMPARISON OF EXPERIMENT RESULTS WITH SIMULATION RESULTS

Detailed laboratory investigation of multi-group radiation transfer enables the verification of radiation-hydrodynamics predictions of macroscopic radiation flows. The experimental data of supersonic transport in low-density foam are good to check the prediction of radiation transfer without perturbation of hydrodynamics in time interval that the experiments last.

Using the temporal behavior of radiation, temperature monitored from LEH at angle 30° relative to the hohlraum axis as the input of radiation for simulation, we simulated the above experiments with LARED-R-1 and a post-processing program. The fluxes of 210 eV and 420 eV photon groups, breaking out from the far end of the foam with different lengths, and reaching the XSC are calculated. Since the exposure of XSC to incoming photon flux can not be absolutely calibrated, the exposure of XSC is normalized to one, so are the calculated fluxes of 210 eV and 420 eV photon group. Figure 9 shows the comparison of simulation results with experiment data. They fit well with each other except in the rising period. As mentioned by (Back *et al.*, 2000*a* or 2000*b*), the rise time of the emission is expected to be the time it takes the photon group to propagate through approximately one free path of that photon group. The opacities of CH calculated by different atomic codes, average atom, UTA, and DTA have been used to count for the rising time difference between the experiments and numerical simulation. We still cannot explain the difference.

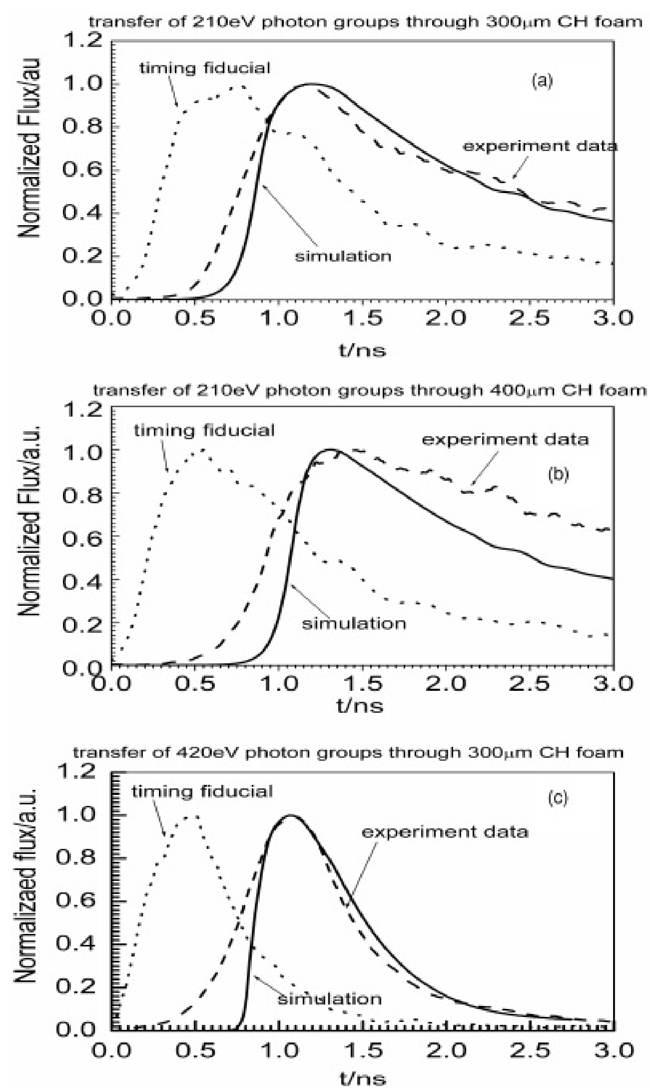

Fig. 9. The simulation results are compared with experimental results. (**a**) The flux of 210 eV breaks through the far end of CH foam cylinder with length 300 μm. (**b**) with length 400 μm. (**c**) The flux of 420 eV breaks through the far end of CH foam cylinder with length 300 μm. The Dot lines show flux from fiducial timing hole. The Dashed lines show flux from far end of foam cylinder. The solid lines show flux reaching the XSC given by simulation. All fluxes are normalized to 1.

https://doi.org/10.1017/S0263034606060654 Published online by Cambridge University Press

5. SUMMARY

The radiation transfers in low-density and low-Z medium should be described by a multi-group model. The profile of plasma temperature and energy deposition predicted by a multi-group model is different from that predicted by a one-group model. Experiments had been done in laboratory using radiation produced by high power laser beams to measure the transfer times of two photon groups through low-density CH foam. The two photon groups, 210 eV and 420 eV, were used to demonstrate characters of multi-group transport within a medium. The CH plasma is optically thin to 210 eV photon group and the external radiation source radiation passes through the heated material to heat the ionization front, causing it to have a preheat part ahead, while with a 420 eV photon group, the CH plasma is optically thick, the external radiation source radiation is absorbed, and reemitted many times before reaching the ionization front. The reemission of X-ray from a heated target plays a crucial role in dynamics of the main part of the ionization front. Distinguishable transfer time delay of the two-photon groups through the foam was observed in experiments, which witnessed the multi-group transfer behavior. Those carefully designed experiments allow us to conduct systematic research on high-temperature radiation wave propagation in a medium.

ACKNOWLEDGMENTS

This work was performed under the auspices of the National Science Foundation of China (No. 10575013) and the National High-Tec Inertial Confinement Fusion Committee of China.

REFERENCES

Afshar-rad, T., Desselbeger, M., Dunne, M., Edwards, J., Foster, J.M., Hoarty, D., Jones, M.W., Rose, S.J., Rosen, P.A., Taylor, R. & Willi, O. (1994). Supersonic propagation of an ionization front in low density foam targets driven by thermal radiation. *Phys. Rev. Lett.* **73**, 74.

Apruzese, J.P., Davis, J., Whitney, K.G., Thornhill, J.W., Kepple, P.C. & Clark, R.W. (2002). The physics of radiation transport in dense plasmas. *Phys. Plasmas* **9**, 2411.

Back, C.A., Bauer, J.D., Hammer, J.H., Lasinski, B.F., Turner, R.E., Rambo, P.W., Landen, O.L., Suter, L.J., Rosen, M.D. & Hsing, W.H. (2000*b*). Diffusive, supersonic x-ray transport in radiatively heated foam cylinders. *Phys. Plasma* **7**, 2126.

Back, C.A., Bauer, J.D., Landen, O.L., Turner, R.E., Lasinski, B.F., Hammer, J.H., Rosen, M.D., Suter, L.J. & Hsing, W.H. (2000*a*). Detailed measurements of a diffusive supersonic wave in a radiatively heated foam. *Phys. Rev. Lett.* **84**, 274.

Canaud, B., Fortin, X., Garaude, F., Meyer, C. & Philippe, F. (2004). Progress in direct-drive fusion studies for the Laser Megajoule. *Laser Part. Beams* **22**, 109–114.

Castor, J.I. (2004). *Radiation Hydrodynamics*. New York: Cambridge University Press.

Danson, C.N., Brummitt, P.A., Clarke, R.J., Collier, I., Fell, B., Frackiewicz, A.J., Hawkes, S., Hernandez-Gomez, C., Holligan, P., Hutchinson, M.H.R., Kidd, A., Lester, W.J., Musgrave, I.O., Neely, D., Neville, D.R., Norreys, P.A., Pepler, D.A., Reason, C., Shaikh, W., Winstone, T.B., Wyatt, R.W.W. & Wyborn, B.E. (2005). Vulcan petawatt: Design, operation and interactions at $5 \times 10^{(20)}$ $\mathrm{Wcm}^{(-2)}$. *Laser Part. Beams* **23**, 87–93.

Feng, T., Lai, D. & Xu, Y. (1999). An artificial iteration method for calculating multi-group radiation transfer problems. *Comp. Phys.* **16**, 199.

Feugeas, J.L. (2004). A hierarchy of nonlocal models for the radiative transfer equation. *Laser Part. Beams* **22**, 121–127.

Hoarty, D., Barriger, L., Vickers, C., Watt, R. & Nazarov, W. (1999). Observation of ionization fronts in low density foam targets. *Phys. Rev. Lett.* **82**, 2171.

Jungwirth, K. (2005). Recent highlights of the PALS research program. *Laser Part. Beams* **23**, 177–182.

Lan, K., Feng, T., Lai, D., Xu, Y. & Meng, X. (2005). Study on two-dimensional transfer of radiative heating wave. *Laser Part. Beams* **23**, 275.

Limpouch, J., Demchenko, N.N., Gus'Kov, S.Y., Gromov, A.I., Kalal, M., Kasperczuk, A., Kondrashov, V.N., Krousky, E., Masek, K., Pfeifer, M., Pisarczyk, P., Pisarczyk, T., Rohlena, K., Rozanov, V.B., Sinor, M. & Ullschmied, J. (2005). Laser interactions with low-density plastic foams. *Laser Part. Beams* **23**, 321–325.

Marshak, R.E. (1958). Effect of radiation on shock wave behavior. *Phys. Fluids* **1**, 24.

Massen, J., Tsakiris, G.D., Eidmann, K., Foldes, I.B., Lower, Th., Sigel, R., Witkowski, S., Nishimura, H., Endo, T., Shiraga, H., Takagi, M., Kato, Y. & Nakai, S. (1994). Supersonic radiative heat waves in low-density high-Z material. *Phys. Rev. E* **50**, 5130.

Mihalas, D. & Mihalas, B.W. (1984). *Foundations of Radiation Hydrodynamic*. New York: Oxford University Press.

Minguez, E., Rodriguez, R., Gil, JM., Sauvan, P., Florido, R., Rubiano, J.G., Martel, P. & Mancini, R. (2005). Opacities and line transfer in high density plasma. *Laser Part. Beams* **23**, 199–203.

Philippe, F., Canaud, B., Fortin, X., Garaude, F. & Jourdren, H. (2004). Effects of microstructure on shock propagation in foams. *Laser Part. Beams* **22**, 171–174.

Pomraning, G.C. (1966). *The Equations of Radiation Hydrodynamics*. Oxford, UK: Pergamon Press.

Zel'dovich, Y.B. & Raizer, Y.P. (1966). *Physics of Shock Waves and High Temperature Hydrodynamic Phenomena*. New York: Academic.