Determination of the Hohlraum M-band Fraction by a Shock-Wave Technique on the SGIII-Prototype Laser Facility

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The proposal of simultaneously determining the hohlraum peak radiation temperature T_R and M-band fraction f_M by shock velocity measurement technique [Y. S. Li *et al.* Phys. Plasmas **18**, 022701 (2011)] is demonstrated for the first time in recent experiments conducted on SGIII-prototype laser facility. In the experiments, T_R and f_M are determined by using the observed shock velocities in Al and Ti. For the Au hohlraum used in the experiments, T_R is about 160 eV and f_M is around 4.3% under a 1 ns laser pulse of 2 kJ. The results from this method are complementary to those from the broadband x-ray spectrometer, and the technique can be further used to determine T_R and f_M inside an ignition hohlraum.

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In indirect drive inertial confinement fusion (ICF), intense laser power or charged particle beams heat the interior of hohlraums which are often made of high-Z materials to generate soft x rays. These x rays, often characterized by a radiation temperature, are used to produce an ablation drive that compresses the D-T fuel capsule placed at the center of the hohlraum, driving it to ignition and burn [1,2]. However, it is important to notice that the concept of radiation temperature just provides an approximate description of the hohlraum x-ray flux. The x-ray flux absorbed by the capsule contains not only the soft x rays emitted from the hohlraum wall, but also the higher energy x rays (mainly M band of wall material) that originated from the laser spots on the wall, especially for a Au hohlraum. The M-band (> 2 keV for Au) radiation flux may preheat the capsule and seriously affect the implosion characteristics [3]. Accurate knowledge of the x-ray flux, especially the Au M-band fraction f_M in the total flux, inside the hohlraum is crucial to ICF ignition capsule design. There have been many works engaged in the determination of f_M [4–6]. In the experiments, f_M is usually deduced from the data of a broadband x-ray spectrometer (SXS [7,8]). However, it is hard for SXS to obtain a real f_M inside hohlraum, because the radiation flux measured by the SXS depends strongly on the observation direction and is usually influenced by the cold plasmas outside the hohlraum and the shrinking of the laser entrance holes [1].

The shock velocity measurement technique is widely used to determine the peak radiation temperature T_R inside a hohlraum [9–11]. This technique utilizes streaked optical pyrometers (SOPs) to observe the thermal luminescence that occurs when a strong, x-ray ablation-driven shock wave breaks through the surface of a well-characterized witness material. By measuring the shock wave velocity V_s in a witness plate mounted on the hohlraum wall, T_R can be determined via a scaling relation of T_R with V_s. Generally, the shock scaling is obtained from the simulations by using a radiation source of Planckian distribution [9,12]. However, the opacity is frequency dependent, so V_s should be related to the spectrum of the radiation source and the relation is different for different witness materials. When the M-band flux in the radiation source is obviously higher than the amount in the Planckian spectrum, the shock velocity in a witness material depends not only on T_R, but also on f_M. According to our studies, the variations of the opacity with frequency in Al and Ti are quite different [13]. For Al, the opacity is low in the regions of the O band ($n = 5$ of Au, radiations at about 450 eV) and N band ($n = 4$ of Au, radiations about 800 eV) but high in the M-band region. It means that there are strong absorptions in the M-band region for Al. However, for Ti, the strong absorptions appear in the regions of the O band and N band. Therefore, the influences of the M-band fraction on the shock wave behaviors is different in Al and Ti. Based on these results, we proposed a method for simultaneously determining T_R and f_M in hohlraums by using the observed shock velocities in two kinds of shock wave witness materials [13].

In this Letter, we report on the recent experiments that demonstrate for the first time the proposal of determining simultaneously T_R and f_M inside a Au hohlraum by using the shock velocity measurement technique with two witness materials of Al and Ti. The experiments are conducted on the SGIII-prototype laser facility [7] consisting of eight laser beams at 0.35 μm, and the laser beams simultaneously irradiate hohlraum from two ends at an incidence cone of 45° angle. In the experiments, a constant power (flattop) laser pulse of 1ns with 150 ps rising and falling times is used. The laser energies are around 2 kJ. The laser spot size at the hohlraum wall is about 250 μm $\times$ 350 μm, and the peak laser intensity is about 2.8×10^{14} W/cm^2. In order to obtain a good radiation uniformity on the witness, it is required that there are no laser spots on the inner surface of samples. Hence, we design a hohlraum with a 2.1:1 length to diameter ratio. The hohlraum is 1 mm in diameter and 2.1 mm in length, with a 25 μm thick wall and one laser entrance hole (LEH) of 0.8 mm diameter at each end.

The step-shaped witness plates Al and Ti are used in the experiment to provide the average shock velocities. The shock velocities in Al and Ti should be measured in the same experimental shot in order to determine simultaneously T_R and f_M inside a hohlraum. For this purpose, the two witness plates Al and Ti are mounted over a 0.6 mm $\times$ 0.45 mm diagnostic hole which is at the middle of the hohlraum, as shown in Fig. 1. The primary diagnostic is two SOPs to respectively view the emissions of ~300 nm UV light emitted as the shock wave breaks out at the exterior surfaces of Al and Ti. In the experiments, we also use a SXS to measure the x-ray flux emitted from the hohlraum through a LEH at 20°. The data of the SXS are used to compare with the results of shock velocity measurement.

Under the x rays generated by the 1 ns flattop laser pulse, the shock velocity in a witness plate is unstable until the radiation temperature reaches its peak. In order to observe the stable shock velocities, the steps of Al and Ti are carefully designed by using our one-dimensional radiation transport hydrodynamical code RDMG [12,14]. According to the calculation results, the two steps are taken as 25 μm and 40 μm for Al, and 20 μm and 30 μm for Ti, respectively. These thicknesses are designed for catching the stable shock velocity initiated by a radiation source of 160 eV.

Prior to the shock velocity measurement, we checked the uniformity of the x rays over the diagnostic hole. We use a SOP to view the optical emission when the shock wave arrives at the exterior surface of an Al witness plate with uniform thickness. The observed result shows an excellent uniformity of x rays over the whole diagnostic hole.

The step thicknesses of Al and Ti targets were measured via a dual active confocal laser contouring measurement [15] before the experiments. With this detailed thickness information and the breakout time interval provided by the step images of SOP, we can obtain an averaged shock velocity. However, this shock velocity is merely a nominal velocity since the movement of the exterior surfaces of witness plates due to the preheat effect [3,13,16] cannot be detected by SOP. Hence, we perform a post-experiment calculation and compare the measured breakout time intervals with the calculated results under radiation sources with various groups of (T_R, f_M). When the calculated breakout time intervals of both Al and Ti steps under a radiation source with a group of (T_R, f_M) agree with the observations, this group of (T_R, f_M) is determined the hohlraum peak radiation temperature and M-band fraction which are *felt* by the samples.

Because the temporal behavior of the input x rays used in the calculations may influence the precision of the determined T_R and f_M, we therefore studied the sensitivities of shock velocity to x-ray temporal behavior by simulations. We considered two kinds of input x-ray temporal behaviors, one is the experimental SXS's data, and the other is the LARED-H code simulation result [7]. As a result, the shock velocities are almost the same under the two kinds of temporal behaviors. In our post-experiment calculations, we adopt the time behavior of x rays obtained from the measurement data of the SXS, as shown in Fig. 2. The input spectrum used in the calculations mainly

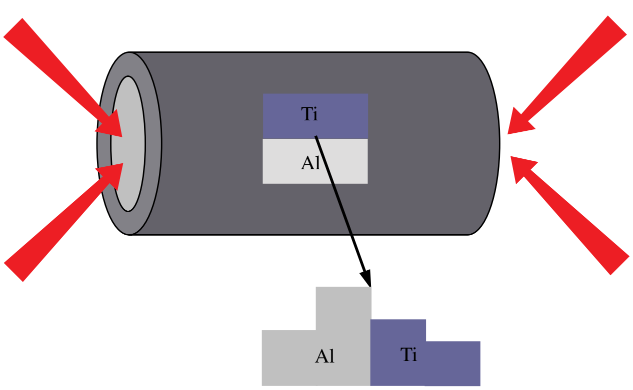

FIG. 1 (color online). Schematic view of the experimental setup. The step witness plates Al and Ti are mounted over the diagnostic hole which is located at the middle of hohlraum.

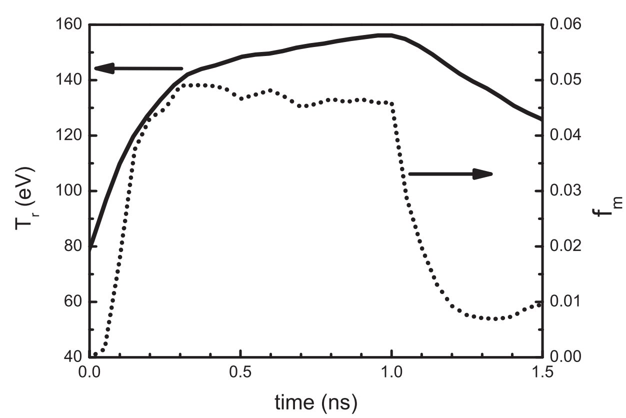

FIG. 2. The temporal behaviors of radiation temperature and the M-band fraction used in the calculations.

TABLE I. The observed nominal shock velocities V_s in Al and Ti witness plates.

Laser energy	2.08 kJ	2.15 kJ	2.17 kJ
V_s in Al	34.15 ± 0.68 km/s	34.76 ± 0.70 km/s	34.76 ± 0.70 km/s
V_s in Ti	22.69 ± 0.45 km/s	24.09 ± 0.48 km/s	23.69 ± 0.47 km/s

includes two parts. The part of lower frequency range is in the Planckian distribution, mainly contributed by the bremsstrahlung radiation, O-band and N-band emission from hohlraum wall, and the part of higher frequency range is in the Gaussian distribution, mainly contributed by the M-band radiation. More detail about this spectrum shape was described in Ref. [13].

During the experimental campaign, three successful shots are performed, with laser energies around 2 kJ. The nominal shock velocities in Al and Ti obtained from SOP data are listed in Table I. The typical SOP images obtained from step-shaped Al and Ti samples are shown in Fig. 3. Time runs from up to down. It is clearly seen that the intensity of emission from the exterior surface increases strongly when the shock wave breaks out at the surface. As shown in Fig. 3, the peak radiant intensities at the thin step breakouts are obviously higher than the intensities at the thick step breakouts. According to our post-experimental simulations, this is caused mainly by the fact that the shock strength is higher at the thin step than at the thick step.

Taking the shot of laser energy 2.08 kJ as an example, here we present our ways to find out T_R and f_M at measured shock velocities in Al and Ti. There are two kinds of ways we usually use. In the first way, (1) we use RDMG to calculate the shock velocities in Al and Ti under the radiation sources with given ranges of T_R and f_M, but only taking sparse groups of (T_R, f_M); (2) we obtain V_s^{Al} and V_s^{Ti} contours in T_R/f_M plane, remembering that the contour lines are obtained by utilizing the interpolation, here V_s^{Al} and V_s^{Ti} are measured shock velocities respectively for Al and Ti; (3) the intersection of the V_s^{Al} and V_s^{Ti} contour lines provides an initial value of T_R and f_M for further detailed calculations; (4) finally, we gradually adjust T_R and f_M in the calculations until the calculated shock velocities equal to the observed shock velocities,

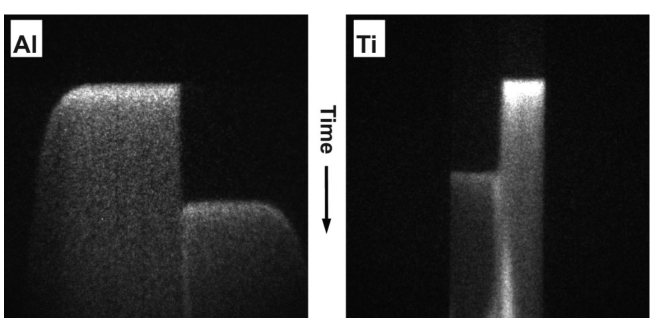

FIG. 3. The SOP images obtained from step-shaped Al and Ti witness plates.

and the final T_R and f_M are the hohlraum peak radiation temperature and M-band fraction which are *felt* by the samples. In the second way, (1) we use RDMG to calculate the shock velocities in Al and Ti under the radiations sources with numerous groups of (T_R, f_M) in given ranges of T_R and f_M; (2) the intersection of the contour lines of V_s^{Al} and V_s^{Ti} in T_R/f_M plane directly gives the final T_R and f_M.

In Fig. 4, we present the contour lines of V_s^{Al} and V_s^{Ti} in T_R/f_M plane, which is obtained by the second way. As shown, the shock wave behaviors in Al and Ti are obviously different as the increase of f_M, the V_s^{Al} contour dropping slowly while the V_s^{Ti} contour dropping sharply. Their intersection gives $T_R = 159.5$ eV and $f_M = 0.043$, the peak radiation temperature and M-band fraction in our hohlraum under a 2.08 kJ laser. Notice that the M-band fraction is only around 0.1% in the Planckian spectrum of 159.5 eV, so our hohlraum radiation is obviously harder than the Planckian distribution. Further considering the 2% uncertainty of shock wave velocity measurement, we have $T_R \approx 159.5 \pm 2.5$ eV and $f_M \approx (4.3 \pm 1.2)\%$. Usually, the opacity error should be taken into account. However, Al is a standard material and the atomic number of Ti is close to Al. Hence, the opacity error of Ti should be small and we neglect it here. In the future, we will design

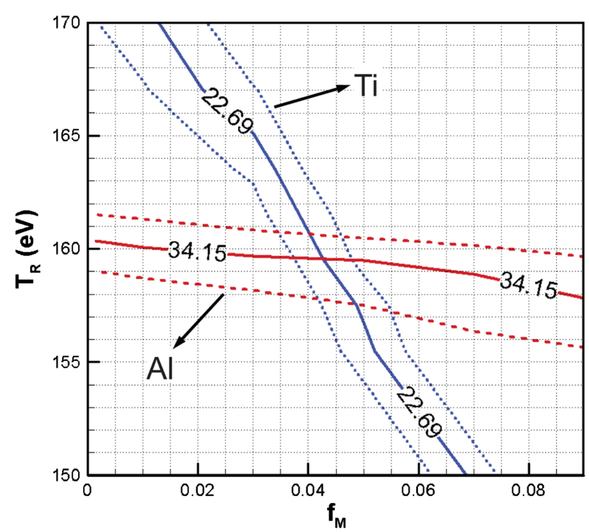

FIG. 4 (color online). Contour lines of V_s, in km/s, in Al and Ti in the T_R/f_M plane. The solid lines are observed shock velocities, and the dashed lines are obtained after considering the 2% error of shock velocity measurement. The intersection of the solid lines provides the value of T_R and f_M, and the intersections of dashed lines give their errors.

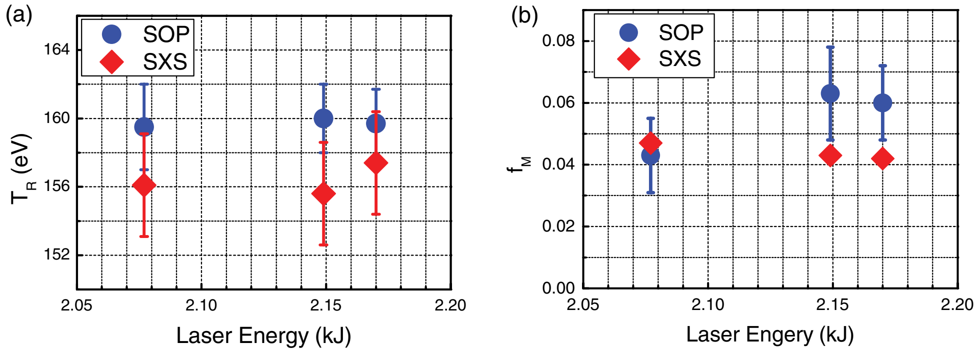

FIG. 5 (color online). The peak radiation temperature T_R (a) and the M-band fraction f_M (b) determined by the shock velocity measurement technique and measured by the SXS under different laser energies.

experiments to estimate the opacity error of Ti, and then consider it in our calculations.

For comparison, we present in Fig. 5 the peak radiation temperature and M-band fraction determined by a SOP and SXS. Here, the 3% uncertainty of the SXS measurement on T_R is taken into consideration. The uncertainty of SXS on f_M has not been determined yet. As indicated in Fig. 5, although T_R and f_M determined by the SOP agree with that from the SXS after considering the measurement errors, the radiation flux incident on the interior surfaces of Al and Ti placed at the hohlraum wall is slightly higher and harder than that *seen* by the SXS through LEH at 20°, except for the shot at 2.08 kJ, in which f_M from the two ways are quite close. Here, the shrinking effect of the LEH [1], which may lead to a smaller radiation flux out of LEH, is not taken into account in the SXS measurement. The M-band fraction of about 5% means that the radiation field inside the hohlraum is not in Planckian distribution, though the temperature of 160 eV is relatively low.

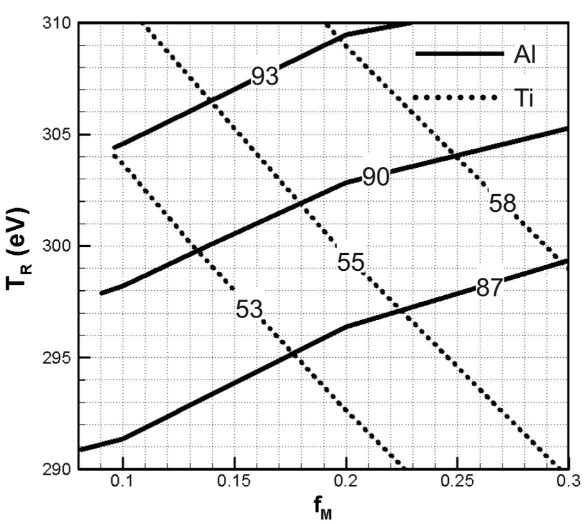

FIG. 6. The shock velocity (in km/s) contours of Al and Ti in the T_R/f_M plane. The range of T_R is 290–300 eV, and f_M is up to 30%.

We also calculate the shock velocities in Al and Ti under radiation temperature around 300 eV, the temperature range of concern for ignition study in inertial fusion science. As shown in Fig. 6, the shock velocity contours of Al increase as f_M at 290 to 310 eV, while those of Ti decrease. Hence, this method of simultaneously determining T_R and f_M by measuring shock velocities in Al and Ti can also be applied to an ignition hohlraum.

In summary, we have demonstrated for the first time the proposal of determining the peak radiation temperature T_R and M-band fraction f_M inside a hohlraum by using the shock velocity measurement technique in recent experiments conducted on the SGIII-prototype laser facility. Two materials Al and Ti are used as the witness materials in the same experimental shot. For the hohlraum used in the experiments, the peak radiation temperature is about 160 eV and the M-band fraction is about 4.3% under a 2 kJ laser energy. The results indicate that the radiation field inside the hohlraum is not in Planckian distribution even though the temperature is relatively low. The results obtained by this technique provide a comprehensive measurement of Au M-band flux from all directions within the hohlraum. This technique can be also applied to determine the M-band fraction inside an ignition hohlraum and provide reference data for successful ignition capsule design.

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