Temperature Measurements of Laser Heated Cavities

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Absolute soft x-ray measurements on laser heated gold cavities (0.25 – 1 mm diam.) yield brightness temperatures $> 10^6$ K. Comparison with theoretical work shows that the temperature in the cavity is determined by the diffusive loss of radiation into the wall.

The heating of small cavities with pulsed laser or particle beams makes it possible to study phenomena of high-temperature radiation hydrodynamics and the state of matter at very high pressure, i.e. the physics of stars, for the first time in the laboratory [1].

In this note we report preliminary results of temperature measurements made with gold cavities irradiated by 60 – 100 J/300 ps pulses from the iodine laser Asterix III at wavelengths of $\lambda = 1.3\ \mu$m $(1\ \omega)$ and $\lambda = 0.44\ \mu$m $(3\ \omega)$. Cavities with 250 – 300 μm diam. and 1000 μm diam. were used. A 280 μm diam. cavity (with entrance hole for the laser beam and two diagnostic holes) as well as the geometry of irradiation and observation are shown in the insets of Figure 1. The fraction of laser radiation rejected by the cavity target was monitored with an integrating box fitted into the experimental chamber. Absolute measurements of the x-ray radiation emanating through the diagnostic holes were made with a transmission grating spectrometer (TGS) and with two x-ray sensitive photodiodes (XRD). The TGS employed a 1000 lines/mm free-standing gold transmission grating [2] integrated into a 25 μm diam. pinhole, thus providing spectral and spatial resolution. The spectra were registered on Kodak 101-01 film, digitized on a 2 D densitometer and computer unfolded using the film calibration data obtained recently in our laboratory [3]. The two XRDs (copper cathode, rise-time ~ 340 ps) received either unfiltered (XRD 1, open) or filtered radiation (XRD 2, 2 μm Makrofol filter). A brightness temperature was derived from both measurements. The radiation time was measured independently with an x-ray streak camera to be 550 ps. The measured temperatures are shown in Fig. 1 versus the absorbed flux $S_L = E_{abs}/A\tau_L$, i.e. the absorbed laser power E_{abs}/τ_L averaged over the inner surface A of the cavity (τ_L the laser pulse duration). It is seen that the measured brightness temperatures increase with the absorbed flux and reach values up to $\sim 1.3 \times 10^6$ K at $S_L \cong 3 \times 10^{13}$ W cm^{-2}. The independent methods yield temperatures which agree rather well.

Following [1] the temperature in the cavity is determined by the radiative heat loss to the ablative heat wave (AHW) [4] penetrating the wall of the cavity. Taking into account recent opacity calculations for gold [5] which suggest a scaling $l_R = A_l T^j v^{\mu'}$ for the Rosseland mean free path ($A_l = 2.76 \times 10^{-10}$ g cm^{-2} K^{-1}, $j = 1$, $\mu' = 1$, v is the specific volume), but following otherwise [4] (see in particular Table 1 and Appendix) one arrives at the temperature scaling

$$T/\mathrm{K} = 3.6 \times 10^3\,[S_v/(\mathrm{W\,cm^{-2}})]^{4/13}\,(t/\mathrm{s})^{2/13}\,. \qquad (1)$$

Here S_v (in the terminology of [4]) represents the net heat flux into the AHW. In the following we shall assume $S_v = \alpha\, S_L$ where α is an empirical coupling parameter. If $\alpha < 1$, a fraction of the absorbed laser flux does not, or at least not instantaneously, feed the radiation wave but is stored elsewhere in the cavity. The storage of energy in the optically thin laser-produced plasma formed in the cavity, or preheat losses into the wall are possibilities in this respect.

The assumption of local thermodynamic equilibrium (LTE) between radiation and matter made in [1, 4] is only of marginal validity for the modest temperatures achievable with our relatively low energy laser source. This has the consequence that the spectrum of the thermal radiation in the cavity will deviate from a Planckian one and its intensity will be less than predicted. In an attempt to obtain more realistic predictions for the observed radiation we first have calculated the hydrodynamic flow by the AHW-model in the LTE approximation [4]. Then, using the profiles of temperature and density determined in this way we have calculated the radiated spectrum by solving the radiation transport equation [5]. The calculated spectra (with peaks at ~ 20 Å and 40 – 50 Å, attributed to transitions in the N and O shell of gold) agree well with the measured ones. In Fig. 1 we have plotted the brightness temperature T_B derived from these calculations and the experimental data. In addition the temperature from (1), which is now identified with the matter temperature T_M is shown for $\alpha = 1$.

The highest temperatures are reached with small cavities, where absorbed average source fluxes S_L above 2×10^{13} W cm^{-2} could be reached with the available laser energy. Framing shadowgraphy showed rather uniform expansion of thin walled cavities of this size indicating a correspondingly uniform energy deposition inside the cavity. A coupling coefficient to the radiative heat wave α between 0.3 and 0.8 seems to be appropriate. This is not unexpected because the loss of energy into nonradiative channels, like fast electrons into deep lying, cold wall layers or the transfer of energy to the hot, electron conduction dominated laser plasma generated in the cavity have been entirely neglected in the AHW model. Whereas

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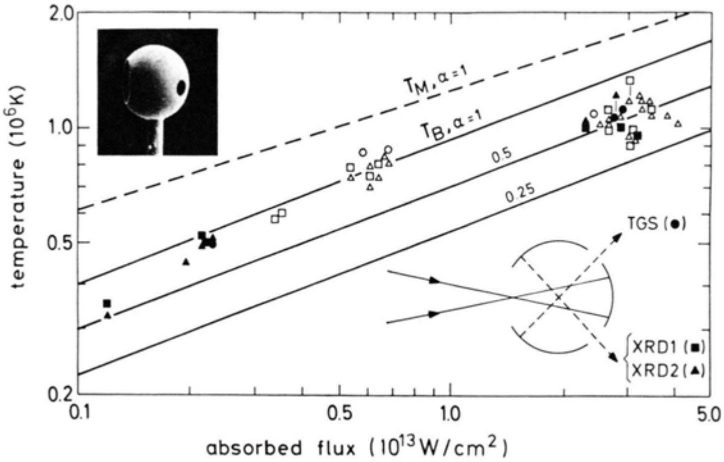

Fig. 1. Laser heating of gold cavities of 1 mm diameter (S_L below 10^{13} W cm^{-2}) and 250 – 300 µm diameter (S_L above 10^{13} W cm^{-2}). Full and open experimental points correspond to measurements at $\lambda = 0.44$ µm and $\lambda = 1.3$ µm, respectively.

the first mechanism has not yet been investigated quantitatively, the existence of a rapidly expanding plasma is inferred from the reduced total absorption of ~ 0.3 measured with the small cavities (> 0.8 for the large cavities), which is attributed to rapid plasma filling of the cavity.

The perfect coupling ($\alpha \cong 1$) observed with large cavities (the large cavities are represented by the experimental points below 10^{13} W cm^{-2}) may be somewhat deceptive; we tend to attribute it to non-uniform energy deposition in the cavity. In our experiments the number of thermal reemissions of the absorbed energy (see [1]) $N_B = \sigma T_B^4 / S_L$, i.e. the measured circulating flux of thermal radiation divided by the absorbed laser flux is only 0.1 – 0.5. Thus the "primary" flux rather than the thermal circulating flux will determine the heating of a given wall element. It seems likely that in the large cavities irradiated at 1 ω the observed wall element was preferentially heated by laser light reflected geometrically from the laser spot on the rear wall of the cavity, and that the intensity in this region was higher than the average intensity S_L.

In conclusion, the heating experiments with small diameter gold cavities have shown that brightness temperatures of about 10^6 K can be reached with laser energies below 100 J. These results are consistent with predictions of a model that considers diffusion of radiation into the wall as the main energy loss mechanism. Effects of plasma filling and entrance hole closure should be avoidable with cavities which are larger than the smallest ones used here. Heating larger cavities to even higher temperatures with the benefit of generating uniform conditions in the cavity would require a more powerful laser.

Finally we would like to mention that cavity heating experiments similar in scope were recently done at ILE Osaka [6].

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