X-ray characterization of laser-driven hypersonic radiative shocks

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Strong radiative shocks often occur in stellar environments and are characterized by high temperature plasma emitting an important fraction of its energy as radiation. They are found in various astrophysical contexts, for instance in the accretion processes of young stars[1], in stellar atmospheres[2], in the interaction of supersonic stellar jets with the interstellar medium[3], and in outflows from supernovae and supernovae remnants[4]. The structure and the dynamics of such plasmas is complex, and experimental benchmarks are needed to provide a deeper understanding of the physics at play. In addition experiments provide unique data for testing radiative-hydrodynamic codes, which in turn are used to model astrophysical phenomena.

Radiative shocks (RS) can be generated using high-power laser facilities[5, 6, 7, 8]. A typical laser irradiance of 10^{14} Wcm^{-2} or more allows to launch radiative shock in a high atomic number gas. The experiments presented here were performed at the PALS kJ high-power laser facility, which is able to produce radiative shocks with velocities of 50-60 km/s in a xenon-filled target at a fraction of a bar [9, 10]. Compared to larger high-power laser facilities (e.g. LULI, Omega), this installation has the flexibility to test new experimental platforms and novel diagnostic techniques.

At high flow velocities, the shocked medium is heated and thus emits radiation, which in turn ionizes and heats the cold unshocked gas. This leads to the creation of an ionization wave or "radiative precursor". These extreme plasma parameters can be observed from numerical simulations, for instance Fig. 1 shows a typical RS in xenon at 0.3 bar moving with a shock speed of 50 km/s. The simulations were obtained using the 1-D radiative-hydrodynamics code MULTI[11]. The electron density varies between 10^{20} cm^{-3} in the precursor and 2×10^{21} cm^{-3} in the post shock.

Optical probing is often used to characterize laser-produced plasmas. However, there are several difficulties that arise in the case of highly dense plasmas. The first one is that visible light cannot propagate though the plasma beyond its critical density, which scales with the probing wavelength as λ^{-2}. For instance for a probing wavelength of 700 nm the critical density is equal to 2×10^{21} cm^{-3}. The second difficulty comes from the strong absorption which scales as λ^3, i.e. just below the critical density. Thus, for high electron densities, the probing beam has to be chosen at a short wavelength, which can be done either with keV backlighting or using soft X-ray lasers[7, 9]. Due to their coherence and brightness, soft X-ray lasers (XRL) open new doors for the study of high-density plasmas, as presented in Mocek et al. and Rus et al. [13, 12].

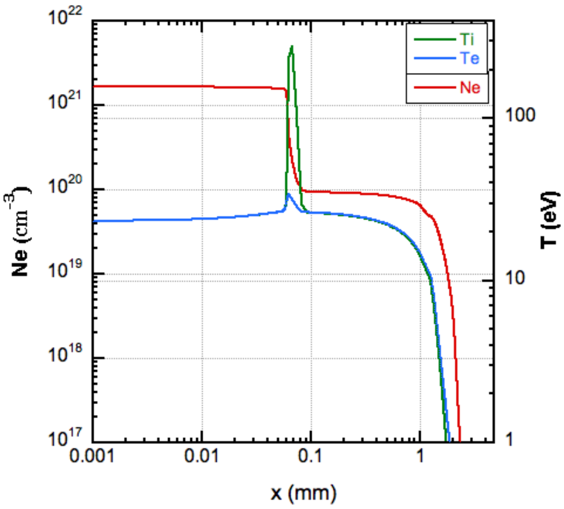

Fig. 1. 1 1-D MULTI simulation of a radiative shock in xenon at 20 ns, in the frame of a uniformly moving piston with a speed of 50 km/s. The initial conditions are a xenon density of $\rho = 1.5\times 10^{-3}$ gcm^{-3} and a temperature of T = 300 K.

The electron density of the precursor has been measured in previous experiments by using time-resolved optical Mach-Zehnder interferometry at a slightly smaller xenon pressure (0.2 bar instead of 0.3 bar) giving an electron density of about 10^{19} cm^{-3}. Other plasma parameters such as ionization and temperature can be investigated by using high- resolution spectroscopy. Recent

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simulations suggest that the shock front emits strongly in the XUV, which heats unshocked cold gas resulting in the formation of the radiative precursor. An attempt to perform such spectroscopic measurements has been performed successfully in recent experiments[8].

The use of such novel techniques such as X-ray lasers together with improvements in soft X-ray mirror technology have made it possible to develop diagnostic techniques that are now suitable for probing plasmas created by high-power lasers[15, 14]. Such enhanced imaging system allows to make a first instantaneous imaging of a radiative shock at 21.2 nm, which is characterized by the presence of both the radiative precursor and the post shock structure. The fast diodes are very useful to record time-and-space resolved plasma self-emission and measure the mean shock velocity. A deep experimental analysis of the spectral signatures[8] of the plasma in various shock regimes along with multidimensional numerical simulations[16, 17] will be the next step for a better understanding of the emission features of highly radiative shocks.

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