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LABORATORY EXPERIMENTS OF RADIATIVE SHOCKS IN THE CONTEXT OF STELLAR ACCRETION.

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Abstract. High-energy lasers are used to simulate astrophysical phenomena in the laboratory. The PALS laser facility, with a typical irradiance of 10^{14} W.cm^{-2}, allows in particular to produce radiative shocks in high atomic number gases. The system is optimized for reaching conditions where the shock is radiative, i.e. it presents a "radiative precursor". This kind of shock is expected to occur during various astrophysical accretion processes. We present preliminary experimental results with emphasis on two diagnostics, namely the study of the laser impact on the target and an instantaneous imaging using an X - ray laser.

Keywords: Radiative shocks, Plasmas, XUV laser, Accretion.

1 Introduction

In Young Stars, the accretion rate is deduced from the photometric signatures of the accretion shocks which are generated by matter falling towards the photosphere at velocities of the order of free fall velocity (∼ 300-500 km/s). These so-called radiative shocks are strong shocks (Mach number, $M >>1$) which are in a regime dominated by radiation. The shock front is heated up to high temperature, and generates intense radiation. If the optical thickness of the medium is sufficiently high, the photons are then absorbed by the unshocked cold medium, leading to an increase in its ionization and temperature, and the development of a "radiative precursor". Radiative shocks are found in many accreting systems, examples includes the initial stages of star formation (Commercon et al. 2011), in already formed Young Stars (Bouvier et al. 2007), or in black hole systems (Chakrabarti & Titarchuk 1995).
In general, the emission properties of radiative shocks and their complex structure is difficult to model, and remains to be fully understood. In this context, experimental studies under controlled conditions are an ideal tool to help unravelling their physics. The most common experimental approach to use high-energy laser installations, to generate a shock in low pressure shock tube containing Xenon gas. Shock waves at velocities of ∼60 km/s have been successfully achieved on several laser installations (Stehlé et al. 2010; Bouquet et al. 2004).

2 Experimental set up

The experiments were performed at the Prague Asterix Laser System (PALS). The installation is capable of delivering an energy up to 1 kJ at the fundamental wavelength of 1.315 μm, with a pulse duration of 0.4 ns. In the present experiment, the laser beam is split into two (AUX and MAIN) beams. The AUX beam (60 J) is focused on a miniaturized shock tube located in a cylindrical vacuum chamber and is used to generate the radiative shock wave. The MAIN beam (500 J) is focused on a Zinc planar target located in a spherical chamber,

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where it generates an X-ray laser (XRL, 3 mJ, 0.2 ns) beam at 21.2 nm (Rus et al. 2002). The XRL beam is sent towards the cylindrical chamber where it passes through the shock tube in order to image instantaneously the shock inside the tube. The delay of the XRL beam respect to AUX beam, measured at the position of the shock tube, is equal to 20 ± 0.05 ns. After travelling through the shock tube where it is absorbed by the Xe density edge located at the shock position, the XRL beam reaches a spherical mirror, which focuses it in an iron pinhole (diameter 500 μm) providing a spatial filtering of the shock self emission. Finally, the XRL beam travels through a thin Aluminium (Al) foil, which suppresses the parasitic visible light, and is recorded onto a cooled CCD (see Fig 1, left). The magnification of the CCD camera (pixel size 13.6 μm) is close to 4.

To control the focusing of the AUX beam, we used two series of diagnostics: first a keV pinhole imaging

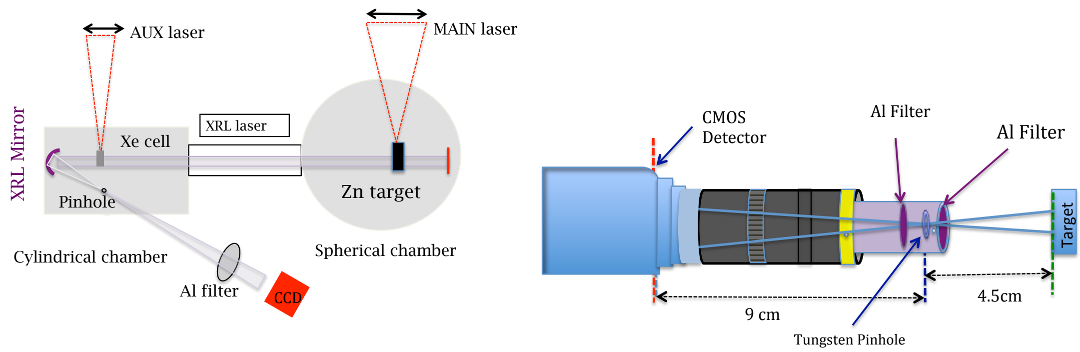

Fig. 1. Left: Schematic experimental set-up. **Right:** Principle of the keV pinhole imaging system.

(magnification 2) controls the position, the size and also the uniformity of the laser beam on the target. This diagnostic (Fig 1, right), includes a Tungsten pinhole (5 μm diameter), located in front of the naked camera CMOS detector (pixel size 6.7 μm). Two Al filters (0.4 μm and 10 μm thick) block the parasitic visible light, and allow to select the relevant keV range photons. The second diagnostics consists in using solid planar Al targets instead of the shock tube, to analyze the size of the crater created by the impact of the AUX beam on metallic surfaces (Gus'kov & Gus'kov 2001; Mora 1982).

The core of the target consists of a shock tubes, with a typical length of 6 mm, and an internal square cross

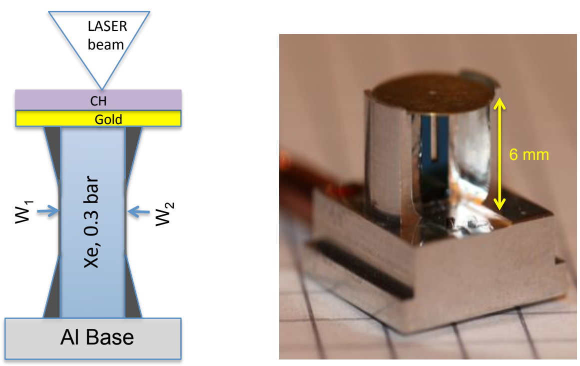

Fig. 2. Left: Target principle; W_1, and W_2 are two Si_3N_4 windows. **Right:** Image of the target.

section of 0.4×0.4 mm^2. The tube is filled in *situ* with Xenon (at a pressure of 0.3 bar). The tube is closed at one end by a 10 μm thick polystyrene (CH) foil acting as a piston, hence the ablation of the plastic by AUX launches, by rocket effect, the piston into the tube. A 0.5 μm thick gold layer is deposited on the polystyrene foil to prevent the X-rays, which are generated during the ablation phase of the polystyrene, to enter into the shock tube (Fig 2, left). The shock tube is closed laterally by two silicon nitrate windows (Si_3N_4), 0.3×0.4 mm^2, each 100 nm thick, with a net transmission of 0.015 at 21.2 nm (`http://henke.lbl.gov/optical_constants/`).

3 Results

3.1 Focusing of the laser

The intensity of the AUX laser on the target surface was modified either by translating precisely the position of the focusing lens (allowing to change the laser spot size) or by using neutral density filter to reduce the laser energy on the target. With these methods, the irradiance on the targets varied between 10^{12} to 10^{15} W.cm^{-2}. To study the crater diameter, we typically used filter with a transmission of 10%. The targets were placed in the beam waist with a reproducibility in the positioning of ± 20 μm.
The size of the craters was measured after the shot, using a high resolution microscope. The keV pinhole camera, monitoring the short duration photon burst, gives the diameter of the corresponding hot spot.
These two diagnostics indicate that the laser spot on the target was about 300 μm.

3.2 XRL imaging

Fig. 3. Snapshot of the shock probed by the XRL laser; the AUX laser coming from the right of the image. The instrumental background is subtracted.

The 21.2 nm XRL was used to probe the radiative shock (Kozlova et al. 2009) with a delay of 20 ns after the interaction between AUX and the target. The spherical mirror was manufactured using a highly polished silica substrate with a multilayer Al/Mo/B4C (theoretical reflectivity of 45% at 21.2 nm). Fig. 3 shows a typical record of a shock wave, in dark gray, propagating from right to left and a black zone which is assumed to correspond to a mixture containing residues of the piston. These results are preliminary and are under analysis.

4 Conclusions

X-ray laser radiography allows analysis of shock waves that would be nearly impossible with optical imaging, due to the expected large value of the electron density. Compared to previous similar results (Stehlé et al. 2012), this new study achieves a noticeable improvement in the quality of the imaging setup by increasing the reflectivity of the spherical mirror, and by reducing the thickness of the Si_3N_4 lateral windows. The shock image was recorded with better contrast. The sensitive keV pinhole imaging monitors not only the position of impact but also helps to estimate the shape and size of the laser beam on the target with a good precision.

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