Applied Surface Science 272 (2013) 69–75

Contents lists available at SciVerse ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

Dynamics of colliding aluminium plasmas produced by laser ablation

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ARTICLE INFO

Article history:
Available online 16 April 2012

Keywords:
Laser plasma
Colliding plasmas
Stagnation
Spectroscopy
Langmuir probe

ABSTRACT

The collision of two aluminium plasmas was investigated by combining both time and space resolved spectroscopy and Langmuir probe measurements. Plasma plumes were produced by a Continuum™ Surelite Nd:YAG Laser System with pulse duration of FWHM of 6 ns and wavelength of 1064 nm, at a laser irradiance of 10^{11} W/cm^2 on slab Al targets. By analyzing the emission spectra, the temporally and spatially resolved electron density and electron temperature at the stagnation layer were extracted, with a time resolution of 10 ns. Data analysis confirms that the electron density of the stagnation layer evolves over a longer timescale than in the single plume case. On the other hand, the temperature trends show that the electron temperature decreases much more rapidly at the stagnation layer than in the case for the single expanding plasma. In addition, a Langmuir probe was used to investigate the properties of the collisional front evolution. The overall experimental results show that colliding laser produced plasmas could be useful in the design of experiments devoted to fusion reaction rate measurements in a low energy domain by including the effect of the electron screening (ES).

1. Introduction

Colliding laser produced plasmas have been investigated in a wide range of laser irradiance regimes (10^{10}–10^{15} W/cm^2) and for several purposes: by employing them as possible fuels for ICF-inertial fusion confinement or in order to reproduce, on a laboratory-scale, astronomical processes as for example collisionless shock waves production [1,2]. In a low laser energy regime (10^{11}–10^{12} W/cm^2) some studies have already been made by different authors in order to study the physical interaction between two counter-propagating plumes (called seeds) expanding at a distance of a few mm from each other [3,4]. For these conditions consistently interpenetration between the seeds does not occur and at the interaction region a so-called *stagnation layer* is formed [5]. It can be studied as a third layer of plasma with peculiar properties: the single plasmas rapidly accumulate at the collision region leading to the formation of a dense layer where a high collisional regime is established. The collisional parameter is then $\xi = D/\lambda_{ii} \gg 1$, where D is the distance between the two seeds and λ_{ii} is the Spizter mean free path, given by the formula [5]:

$$\lambda_{ii} = \frac{m_i^2 v_{12}^4}{4\pi e^4 Z^4 n_i ln\Lambda_{12}} \quad (1)$$

where v_{12} is the relative velocity of the ions coming from the two plumes, Z is the average charge state of the plasma, n_i is the average plasma ion density and $ln\Lambda_{12}$ is the Coulomb logarithm [6]. Therefore, the characteristics of the stagnation layer depend on the distance between the two seeds and of their dynamics expansion properties and consequently, on the electron and ion densities of the collisional front. The purpose of this work is to demonstrate that colliding plasmas could be used to study fusion reaction rates in a low energy domain and phenomena of astrophysical interest [7,8]. Many large scale phenomena are studied through laboratory plasmas and the results are then related to space plasmas through scale laws. Numerical simulations already demonstrated that laser produced plasmas (LPPs) have the unique property of having high enough ion temperatures to favor a certain number of nuclear fusion events. At the same time, the presence of clouds of cold electrons, provides to a non negligible electron screening factor whose value is similar to the stellar one: it is on the order of 1.2, calculated with the typical density and temperature values of laser plasmas produced at a power density of about 10^{11} W/cm^2. Its weight is on the order of 20% in determining the total number of fusions events [9,10]. Since the ES scales with the ratio of n_e/T_e, in order to have

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http://dx.doi.org/10.1016/j.apsusc.2012.03.119

a consistent screening effect one needs high electron densities and at the same time low electron temperatures: the characteristics of the stagnation layer could be used for this purpose. Hough et al. already demonstrated that at a laser fluence of 1.6×10^3 J/cm^2, the first collision front, observed at ~30 ns, is composed mainly of electrons followed 10 ns later by ionized Al ions. A significant screening effect could be induced from the stagnation of the electrons at the mid-plane collision front which permits the highly charged ions to approach each other quite closely leading to a tight ion stagnation layer [4]. In this paper measurements were carried out with Al colliding plumes, by combining time and spatially resolved spectroscopy and Langmuir probe measurements. Fast imaging and emission spectroscopy measurements were performed in the visible range and revealed detailed information about the dynamics of spectral emission of the atomic species (neutral atoms and ions) which compose the seeds and the colliding region. Moreover, the Langmuir probe measurements permitted us to obtain the time of flight signals (TOF) at the stagnation front: by placing the probe very close to the target surface a *current plateau* was detected in the signals due to the stagnation layer contribution. The geometrical configuration employed to obtain the collision between the two plasmas (*flat-target configuration*) allowed to distinguish and study the properties of both seeds and the stagnation layer.

2. Experimental set-up

The experimental apparatus used in this work is described in detail by Hough in Ref. [11]. The laser is a Surelite III-10 Laser system: it operates at the fundamental wavelength of 1064 nm and emission is in pulsed mode with a maximum energy per pulse of 800 mJ, a FWHM of 6 ns and a maximum repetition rate of 10 Hz. The Laser system was synchronized temporally with the main diagnostic systems using two Stanford DG-535 delay generators with a maximum temporal jitter of 1 ns. All measurements were done at an operating pressure of 1×10^{-6} mbar. The target set-up used to achieve the plumes collision was a flat configuration [12,4]: an acute $\gamma = 1^\circ$ wedge prism that splits the laser beam into two separate beams is then focused on 99.99% pure Al planar targets through an anti-reflection coating plano-convex lens with focal length of $f = 300$ mm and a diameter of 25.4 mm. The obtained spot sizes at the target surface were for each beam on the order of 80–100 μm. The distance between the spots was $D = 2.6$ mm and can be determined by equation:

$$D = f\gamma(n-1) \quad (2)$$

where n is the refractive index of glass. Each of the separate beams created by the wedge prism carries a laser energy of 300 mJ (half of the incident 600 mJ laser pulse energy).

2.1. The imaging system

Fast imaging was spatially, spectrally and temporally resolved. It was realized by employing a gatable Andor ICCD camera with a 1024 × 1024 pixel array and an active area of 12.3 mm × 12.3 mm. A Pentax zoom lens together with an extension tube (to increase the final distance lens-camera) of 500 mm in length, was attached to the ICCD to image the plasma on the camera. The magnification of the system was $M = 1.62X$. To observe the entire bulk plasma radiation emission a broadband short pass interference filter was employed, transmitting all radiation of wavelengths between 300 nm and 950 nm in order to protect the ICCD from any scattered laser radiation. Two narrow bandpass filters centered at 390 nm and at 460 nm, respectively with FWHM of 10 nm and a corresponding transmission efficiency in this region of the 40% and 60% permitted the isolation of the line emission from neutral Al atoms and singly charged Al ions. Images were recorded every

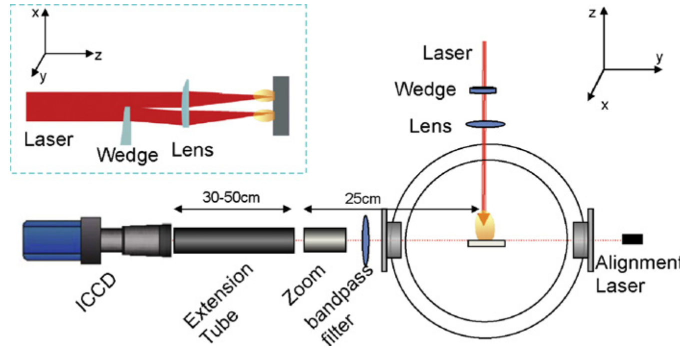

Fig. 1. Schematic diagram of the fast imaging experimental set-up together with scheme used to split the output from the laser into two separate pulses.

10 ns with an ICCD exposure time of 3 ± 1 ns with single shot laser pulses. A schematic diagram of the fast imaging setup is shown in Fig. 1 together with the splitting laser beam scheme.

2.2. Optical emission spectroscopy

Optical emission spectroscopy was realized with a 500*is* Chromex spectrograph. It consists of a Czerny-Turner mount with toroidal focusing mirrors which enabled aberration-corrected flat field imaging and operates with a 1200 grooves/mm diffraction grating with a blazed wavelength of 400 nm and a resolution of 0.07 nm FWHM. The technique is based on the approach of Siegel et al. described in Ref.[13] and was used for colliding plasmas by other authors [14,15]: the plasma focused on the entrance slit of the spectrograph produces at its output a one-dimensional spatial and spectral plume image. The vertical axis corresponds to its expansion direction (z) and the horizontal axis refers to the wavelength λ of the emission species. By placing a gatable ICCD at the spectrograph output, it is possible to obtain simultaneously the spectral and spatial information of the plasma propagation; the temporal evolution is then obtained by gating the ICCD camera [13]. In our case, each spectrum corresponded to the spectral distribution of a horizontal slice of the colliding plasma system, containing the two seed plasmas and the interaction region between them, as shown in Fig. 2a. A relay lens imaging system composed of two achromatic plano-convex lenses L_1 and L_2, respectively of focal length of $f_1 = 15$ cm and $f_2 = 10$ cm was employed to create the plasma image at the entrance slit. By translating the entire spectrograph (and thus the entrance slit with respect to the image of the plasma) in small increments of 500 μm, corresponding to 0.83 mm increments at the plasma formation plane, along the normal direction of the target surface, different slices of the seeds and the stagnation layer were imaged into the spectrograph. In this way accurate spatial resolution of both of their expansion was obtained.

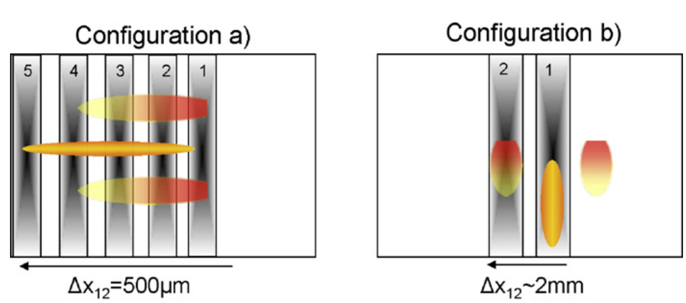

Fig. 2. Schematic diagram of the image of the colliding plasmas at the entrance slit of the spectrograph without (a) and with (b) the use of the Dove prism between L_1 and L_2.