

Jetlike Emission From Colliding Laser-Produced Plasmas

Sivanandan S. Harilal, Mathew P. Polek, and Ahmed Hassanein, *Member, IEEE*

Abstract—We report a large jetlike collimated emission feature from colliding laser-produced plasmas (LPPs). The plasmas are produced by focusing two parallel laser beams on a planar copper target. Time-resolved spectrally integrated emission features in the visible region are recorded using an intensified charge-coupled device camera. Both laser plasmas expanded perpendicular to the target and collided side-on. The jetlike emission has a spatial extension of more than 3 cm and exists in a prolonged time compared with single LPPs.

Index Terms—Colliding plasma, laser-produced plasma (LPP), plasma expansion, plasma images.

I. INTRODUCTION

LASER-produced plasmas (LPPs) are formed by focusing the output pulse from a high-power laser onto a target. The characteristic parameters of these transient plasmas quickly evolve and are strongly dependent on irradiation conditions. Most of the applications of LPPs are centered on using one laser beam and a single target material. Several applications of LPPs involve experimental situations in which collision between plasmas occurs. Relatively recently, laser-produced colliding plasmas have found potentially attractive applications in the field of X-ray lasers, pulsed-laser deposition (PLD), extreme ultraviolet lithography, and generating astrophysical objects in the laboratory frame [1]–[3]. Despite considerable experimental and theoretical progress in the dynamics of single LPPs, little attention has been paid studying the nature and dynamics of laser-produced colliding plasmas. Typically, the LPPs expand into vacuum in a preferential direction perpendicular to the target surface, and the emission features exist only at short distances (< 1 cm) and disappear after $1 \mu\text{s}$ [4]. A laterally colliding plasma scheme showed that emission features are extended in both space and time.

II. EXPERIMENTAL SETUP

For generating the colliding plasma, the fundamental radiation from a Nd:YAG laser (1064 nm, 6 ns full-width at half-maximum) was split into two beams with the help of a 0.5°

wedge prism. The two parallel laser beams were then focused onto a Cu target with spot diameters of $\sim 100 \mu\text{m}$ with a separation of 3 mm. The target was kept in a chamber with a vacuum $\sim 10^{-6}$ torr. Plume imaging was accomplished with an intensified charge-coupled device camera placed orthogonal to the laser beam. A programmable timing generator was used to control the delay time between the laser pulse and the detector system with an overall temporal resolution of 1 ns. The visible radiation from the plasma was integrally recorded in a wavelength range of 350–900 nm.

III. RESULTS

Fig. 1 gives the sequence of images at various times obtained after the onset of plasma formation. These images were recorded at a laser intensity of $3 \times 10^{11} \text{ W/cm}^2$ at each laser focus. The duration of the exposure time sequentially varied from 5 to 50 ns, and each image was obtained from a single laser pulse. The direction of the laser beams are marked with arrows in the figure. The resulting plasmas expand away from the target but stream into each other in a direction parallel to the target surface. When two such plasmas collide, there are two extremes of resulting behavior—the plumes can either interpenetrate or come to a virtual stop to form a high-density hot layer, the so-called stagnation layer. Fig. 1 shows that the stagnation layer appears in the collision region at early times. The stagnation layer initially expands in a direction perpendicular to the target with excellent collimation, and at later times ($> 1 \mu\text{s}$), it starts to laterally expand. The images taken at different times mirror the temporal displacement of the plume front and hence give the velocity of the plume. The jetlike featured emission expands with a velocity $\sim 3.77 \times 10^6 \text{ cm/s}$ until $1 \mu\text{s}$ in a direction perpendicular to the target surface. At later times, the collision region appears to expand in the lateral direction with a much lower velocity ($3 \times 10^5 \text{ cm/s}$). The stagnation layer exists for a very long time compared with the emission from the individual seed plasmas, which ceases at later times ($> 1 \mu\text{s}$).

The emission spectroscopic studies of colliding plasmas showed that, in the earliest times of plasma evolution (< 1000 ns), the spectra mainly contained singly ionized Cu species along the excited neutrals. However, at later times (> 1000 ns), the spectra are predominantly dominated by excited neutrals.

When two plasmas collide, various interactions may arise. For sufficiently low plasma densities and higher expansion velocities, where the ion–ion mean free path exceeds the dimensions of the system, the two plasmas interpenetrate with little collisional interaction. When the ion–ion mean free path

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The authors are with the School of Nuclear Engineering and Center for Materials Under Extreme Environment, Purdue University, West Lafayette, IN 47907 USA.

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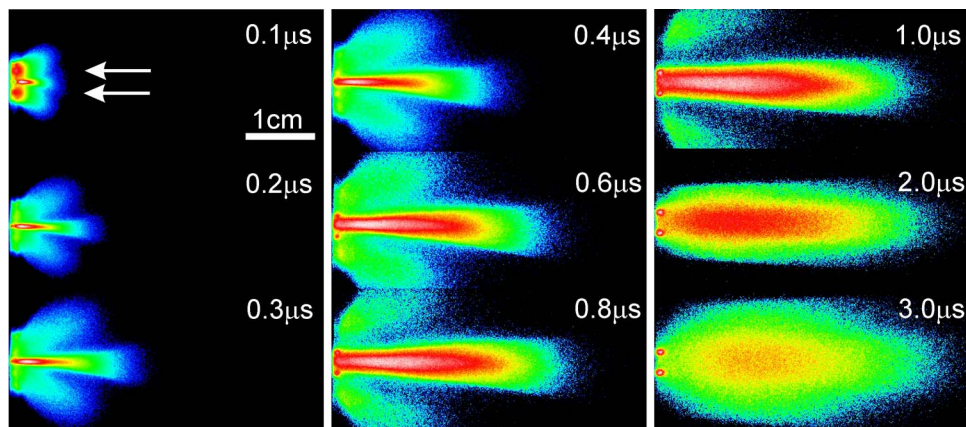


Fig. 1. Images of the plasma jet formed by laterally colliding laser-produced plasmas at various times after the onset of the plasma. Each image is obtained from different laser shots, and all the images are normalized to their maximum intensity for better clarity.

is smaller than the plasma density scale lengths, the region of plasma interpenetration is relatively small, and the plasma stagnates. Moreover, other effects such as space-charge separation and ambipolar diffusion have also been shown to be important factors in the formation of the stagnation layer [5]. The visible images showed that the plasmas attain stagnation at the early times itself. However, at later times, particularly $> 2 \mu\text{s}$, the densities of the plume will be lower, and interpenetration can happen. It should be mentioned that, by controlling the initial parameters of the seed plasmas, we can control the characteristics of the stagnation layer. Stagnation layers offer a new type of plume with a number of significant potential advantages for PLD, laser ion sources, laser-induced breakdown spectroscopy, and short-wavelength light sources.

In conclusion, a jetlike emission feature is noticed in laterally colliding plasmas. Our results showed that the lifetime and the spatial extension of the plasma can be considerably enhanced using a colliding plasma scheme. Advanced computer simula-

tion using HEIGHTS package has also confirmed jet formation as a result of the colliding plasmas [3].

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