The Effect of Wedge Angle on the Evolution of a Stagnation Layer in a Colliding Plasma Experiment

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Abstract. Colliding plasmas are steadily gaining significance in hohlraum studies, pulsed laser deposition and laser-induced breakdown spectroscopy for a number of reasons, not least the levels of control they offer over the properties of the slab of plasma that accumulates at the collision front, i.e. the stagnation layer. We present here some results of a time and space resolved optical-spectroscopic study of colliding plasmas formed at the front surfaces of flat and inclined Cu slab targets as a function of the wedge angle between them for angles ranging from 0° to 180° (i.e., laterally colliding plasmas). Presented here are the kinetics of atomic/ionic spatial distributions throughout the stagnation layers, both of which have been found to vary significantly with wedge angle.

1. Introduction

Although colliding laser produced plasmas are not a new area of study[1], there is renewed interest in a number of international centres [2-15] due to their potential application in inertial confinement fusion [16, 17], pulsed laser deposition (PLD) [18, 19], laser induced breakdown spectroscopy (LIBS) [20,21], and other applications. When two laser-produced plumes collide the outcome usually sits between two extremes. If the so-called seed plasmas have a large relative velocity and low density at the collision front the plasma plumes will tend to interpenetrate. Alternatively, when the relative velocity between the plasmas is small and the density at the collision front is large, plasma constituents will tend to decelerate rapidly leading to the formation of a so-called stagnation layer. This is known as ‘hard’ stagnation, whereas the intermediate regime between interpenetration and hard stagnation is known as soft stagnation. To help determine which regime to expect, one can make use of the collisionality parameter [22,23] defined as

\[ \zeta = \frac{D}{\lambda_{ii}} \]  

(1)

where \( \zeta \) is the separation between the two seed plasmas and \( \lambda_{ii} \) is the ion-ion mean free path given by [22]

\[ \lambda_{ii}(1 \rightarrow 2) = \frac{m_i^2 v_{12}^4}{4 \pi q^4 z^4 n_i m \lambda_{1 \rightarrow 2}} \]  

(2)

where the indices 1 and 2 refer to the individual plasma plumes, \( m_i \) is the ion mass, \( v_{12} \) is the relative collision velocity, \( q \) is the fundamental electronic charge, \( z \) is the average ionisation
state of the plasma, $n_i$ is the average plasma ion density, and $\ln \Lambda_{1 \rightarrow 2}$ is the so-called Coulomb logarithm.

It is clear from equations 1 and 2 that control over seed plasma properties such as $v_{12}$ - and, to a lesser extent, the distance $D$ between them - can yield a significant degree of control over the collisionality parameter $\zeta$, which determines not only the degree of stagnation but also plays a significant role in determining many of the properties of the stagnation layer such as temperature, density, composition, degree of ionisation, geometry, etc. A change of the distance $D$ is a simple experimental task, and by varying the angle of inclination of the seeds we can gain a degree of control over $v_{12}$. Here we present some results of a systematic study of the effects on the stagnation layer when the angular attitude of the target slabs is varied.

2. Experimental Setup

Figure 1, which is split into four parts, shows the setup used for the experiments described in this paper. Figure 1 (a) shows a Surelite III Nd:YAG laser which operates at a wavelength of 1064 nm and generates up to 800 mJ per pulse (reduced to 210 mJ using a Brewster’s window and half-wave plate) in 6 ns FWHM pulses. By passing part of the beam through a wedge prism while the remainder passes over it [24], the beam is split into two parts. It then passes through a lens which focuses each beam to a spot of diameter $\approx 100 \mu m$, as shown in figure 1 (b). The distance between the two foci is related to the lens and wedge prism by:

$$d = f \gamma(n - 1)$$

where $n$ is the refractive index of the wedge prism (here glass with $n = 1.5$), $\gamma$ is the acute angle of the wedge in radians, and $f$ is the focal length of the lens.

A rotating target is used to refresh the target material and is placed inside a vacuum chamber maintained by a turbomolecular pump at a base pressure of $1 \times 10^{-7} \text{ mBar}$. Two seed plasmas are created, which collide to form the stagnation layer (under suitable conditions). Both broadband optical imaging (figure 1 (c)) and spatially and temporally resolved spectroscopy (figure 1 (d)) are carried out simultaneously. Broadband imaging uses a variable zoom lens to focus the image onto an Andor DH534 camera which is mainly used to align and monitor the highly sensitive setup while spectroscopic measurements are undertaken. The setup is described in detail in [25].

Figure 1: Experimental setup for the optical analysis of the interaction region between two laser produced plasmas.
3. Results & Discussion

Information about the evolution of a plasma over time can be obtained by tracking the plume front position as a function of time delay [20,24]. If, instead, we follow the maximum point of the intensity of the emitting atoms and ions - taken to be the brightest part of each emission line (assuming no attenuation due to opacity) - it is possible to trace the movement of each of the species throughout the plume. This is achieved by recording and plotting the intensity at each point along the forward expansion direction of each space and time-resolved spectral line to yield a curve showing the peak of emission intensity for atoms and ions along the plume. Figures 2 and 3 show examples of these plots, obtained by analysis of the Cu I line at 521.82nm and the Cu II line at 508.83nm respectively, revealing the differing movements of each atomic/ionic fluid.

Figure 2: Motion of the peak intensity point of atomic copper (λ = 522 nm) in the stagnation layer.

Figure 3: Motion of the peak intensity point of singly charged copper (λ = 509 nm) in the stagnation layer.

Figure 4 (a) shows the emission image obtained by colliding seed plasmas created on laterally facing (parallel) targets corresponding to a 180° target wedge angle, or the flat configuration. As the two seed plasmas expand, they collide at relatively low velocities along the lateral expansion plane (parallel to the target surface).

Figure 4: Time integrated images of the stagnation layer formed using 3 separate wedge angles: (a) 180°, (b) 140° & (c) 100°.
By employing a 140° wedge-shaped target (figure 4 (b)) the two seed plasmas now collide with a larger component of their forward expansion velocity directed orthogonally (towards each other). The relative collision velocity is thus higher, and the ion-ion mean free path (MFP) becomes larger, resulting in a higher degree of plume interpenetration. Figure 4 (c) shows the case where the wedge angle is decreased to 100°, thus further increasing the degree of plume interpenetration here. The shape of the stagnation layer illustrates the degree of interpenetration in each case, where hard stagnation creates tight and well defined stagnation layers. It is clear from the figures that the most tightly defined stagnation layer is formed in the case of laterally colliding plasma plumes.

As described above, the point of maximum intensity for selected emission lines from Cu atoms and singly charged ions is traced as a function of time. The results are shown in figure 5 for three separate wedge angles (100°, 140° & 180°) at a seed distance of D = 1.3 mm for both neutral atoms and singly charged ions. Shown also is a linear fit to each data set, where appropriate.

![Figure 5: Comparison of the movement of the peak of intensity of neutral emitting atoms and singly charged ions in a stagnation layer generated by focusing two 105 mJ 6 ns laser pulses onto three different wedge systems.](image)

A quick comparison of both graphs reveals that the singly charged ions move at a significantly higher velocity relative to the atoms for all three wedge angles. It is well established that the initial expansion velocity of electrons from the seed plumes far exceeds that of the heavier ions [26]. This leads to the generation of a strong electric field caused by the steep gradient in the spatial distribution of charged particles as the electrons attempt to separate from the ions (ambipolar diffusion). The resulting net field slows the electrons while accelerating the ions, and has little effect on the neutral atoms.

Two mechanisms contribute to growth in the forward expansion direction of the ions in the stagnation layer. Firstly, the time of flight for the material from each seed plasma to reach more and more distant points on the collision plane, and secondly the fact that material that arrived earlier has a component of forward momentum and will thus move outwards along the stagnation layer. A comparison of the velocity of the peak of intensity of singly charged ions is shown in table 1. It can be seen that in the case of the 100° wedge angle in particular, the
orthogonal component does not appear until times \( \geq 60 \) ns, i.e. a linear fit applies only after this time. In this case, interpenetration at the lower layer region is increased; hence growth in the forward expansion direction is not evident until later times. Applying the linear fit to each case, the \( \text{Cu}^{+} \) ion growth rates range from \( 9.2 \times 10^{5} \) cm/s for the case of the 1.3 mm, 210 mJ, 100° wedge case to \( 26.1 \times 10^{5} \) cm/s for the 1.3 mm, 210 mJ flat target case. In the flat target case, the stagnation layer grows predominantly in the forward expansion direction as time progresses. This is supported by figure 4 (a), where the stagnation layer formed is narrow and elongated. There is little or no growth along its lateral dimension, giving a strong indication that the degree of interpenetration is quite low. By comparison, for neutral atomic species, as stated earlier, the average velocity is almost independent of wedge angle at a value of \( \sim 3 \times 10^{5} \) cm/s.

| Target Geometry                  | ions/(cm/s) |
|----------------------------------|-------------|
| 1.3 mm, 210 mJ, 180° Wedge       | 26.1 \times 10^{5} |
| 1.3 mm, 210 mJ, 140° Wedge       | 16.6 \times 10^{5} |
| 1.3 mm, 210 mJ, 100° Wedge       | 9.2 \times 10^{5} |

*Velocity here does not mean expansion rate in the normal sense of plasma plume expansion. Rather it refers to the propagation of the peak intensity value along the stagnation layer as material from the seed plasma plumes reaches the collision plane at a delay determined by the distance to be travelled and the concomitant times-of-flight.*

In summary, the stagnation layer growth is different for separate ionic species, and the growth of each specie throughout the layer is dependent on two mechanisms: accumulation at the collision plane at a rate determined by the time of flight of seed plume species to the collision plane, and the movement of stagnation layer species along the collision plane due to their natural component of forward directed momentum. Thus, for any one wedge angle the atom and ion growth rates are different and hence fluid growth rates in the stagnation layer will be different, as will the initial spatial distribution for each as the layer grows.

### 3.1. Comparison of a Stagnation Layer with a Single Seed Plasma

We have demonstrated above that the properties of the stagnation layer can be controlled in a manner not available to single laser plasma plumes. Both the lifetimes and intensities of spectral lines in laser produced plasmas can be increased by creating relatively moderate density high-energy plasmas which can overcome the problem of flux loss due to opacity, which leads to the attenuation of discrete emission lines with a concomitant reduction in line contrast, signal-to-noise ratio (SNR), and signal-to-background ratio (SBR). The latter is a key parameter in determining the limit-of-detection (LOD) of the LIBS technique. Here we compare with a single plasma plume the stagnation layer of most interest for LIBS, a layer created by the 1.3 mm seed separation, 210 mJ total pulse energy, 100° wedge case, where relatively low species growth rates occur.

Figure 6 shows a comparison of the growth rates of species in a stagnation layer created using the laser and target geometries described above, along with a single plume using the same total pulse energy. The velocity of both the peak of the neutral atom distribution and of the singly charged ion distribution is higher in the case of the single pulse plume, and the ions move at almost twice the velocity in the forward expansion direction. The stagnation layer is confined spatially for a longer period of time which slows its evolution through time and should
Figure 6: Comparison of the movement of the peak of intensity of neutral emitting atoms and singly charged ions for a single pulse plasma created using a 210 mJ total pulse energy with a stagnation layer created using a 100° wedge, 210 mJ total pulse energy and 1.3 mm seed separation. These differences cause the density gradient to be smaller than the single pulse case. Hence one should expect the temperature and density profiles to be more uniform throughout the stagnation layer. This topic will be the subject of a follow-up paper.

4. Conclusions
Spatially resolved and temporally integrated as well as spatially and temporally resolved imaging spectra have been used to study the interaction of counter-propagating laser-produced plasmas. The results presented show a range of different behaviours in the interaction dynamics between each of the plasma plumes for different initial target wedge angles. A study of the progression of the peak of the intensity of singly charged ions along the stagnation layer as a function of time for a range of initial conditions shows that the velocity of ions varies significantly as a function of the wedge angle between the seed plasma plumes. Figure 4 (b) and (c) illustrate the progression from ‘hard stagnation’ to ‘soft stagnation’ of the layer, where the increase in the lateral dimension of the stagnation layer, i.e. the width, and the decrease in length is apparent. The decreasing growth rates of the peak position of singly charged ions (Table 1) as the wedge angle closes confirm this. It was demonstrated that the geometry of the stagnation layer can be controlled by variation of the wedge angle, a property which has implications for double-pulse (DP-) LIBS where the size and shape of the main plasma are important for efficient coupling of laser energy to the plasma.

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