

Dynamics of colliding ablation plumes

H. Sato¹⁾, Y. Hirooka²⁾, K. A. Tanaka¹⁾ and K. Ishihara¹⁾

¹⁾ Graduate School of Eng. & Inst. Laser Eng., Osaka University Suita, Osaka, Japan 565-0871

²⁾ National Institute for Fusion Science, Toki, Gifu, Japan 509-5292

(Received: 20 November 2009 / Accepted: 2 March 2010)

Abstract

Carbon and tungsten have been radiated by 3 ω -YAG laser in the power density range from 2 to 12J/cm²/pulse in a laboratory setup with the main objective of investigating the behavior of cluster/aerosol formation from colliding ablation plumes. Direct ion mass spectrometry of colliding carbon plumes has identified C_n⁺-clusters including C⁺, C₂⁺, C₃⁺, C₄⁺ and C₅⁺. The formation of these C_n-cluster ions has been found to favor relatively low laser power densities. From timing-controlled Langmuir probe measurements for carbon and tungsten, the density decay constants for single plumes have been found to be 1.2 μ s and 4.4 μ s, respectively, whereas colliding plumes have been evaluated to be 1.4 μ s and 5.3 μ s.

Keywords: inertial fusion, ICF target chamber, chamber ablation, ablation plumes, cluster and aerosol formation

1. Introduction

A series of 192-beam implosion experiments have successfully been conducted at NIF [1], based on which the LIFE reactor study will proceed to constructing a fusion-fission hybrid demo reactor in around 2020 [2]. In the LIFE fusion core, DT-pellet implosions take place at 15Hz. In the case of the KOYO-fast reactor study [3], 4 power units will operate at the repetition rate of 4Hz individually. The target chambers of these reactors are currently designed to be either point or axially symmetric. Therefore, one would predict that ablated wall materials in the form of plasma due to the ultra intense radiation of unburned DT particles, CH-pellet debris and X-ray will be transported to aggregate in the center-of-symmetry region, travelling across the chamber. Some of these plasma particles may miss each other to be re-condensed elsewhere in which case one expects an extended wall lifetime, but others collide with each other, which can then lead to cluster/aerosol formation. As a result, subsequent laser beams may be reflected, deflected or scattered, which would effectively limit the implosion repetition rate, and hence reactor performance.

From the reactor operation point of view, therefore, it is of critical importance to understand the interactions behavior between ablation plume plasmas. In the present work, the dynamics of colliding ablation plumes has been investigated with the emphasis of understanding the behavior of cluster formation, using a laboratory-scale setup developed recently for this purpose [4].

2. Experimental

A new experimental setup has been put together, referred to as LEAF-CAP for the Laboratory Experiments on Aerosol Formation by Colliding Ablation Plumes [2].

Employed in this setup is a 3 ω -YAG laser beam (~320mJ/pulse, 6ns, 10Hz), optically split into two equal-power beams and then each line-focused (~0.1mm by ~1cm) to radiate two targets at room temperature in a vacuum chamber (~10⁻⁶ Torr), i.e. a double target setup. Here, the line-focused area is defined by boundaries at which the laser power is attenuated down to 1/e². The power densities referred to in the remainder of this paper are evaluated by this definition. In the present work, the line-focused power density is varied in the range from 2

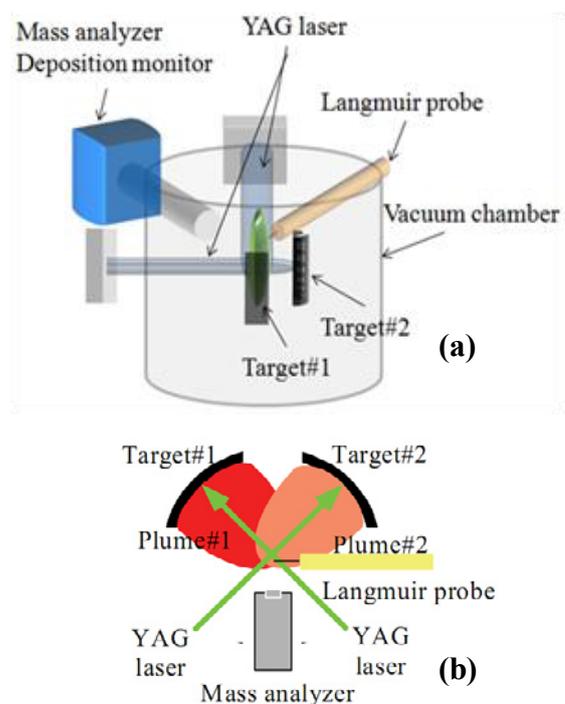


Fig. 1 The LEAF-CAP experimental setup: (a) 3D-layout and (b) 2D-layout.

author's e-mail: sato-hiro@ile.osaka-u.ac.jp

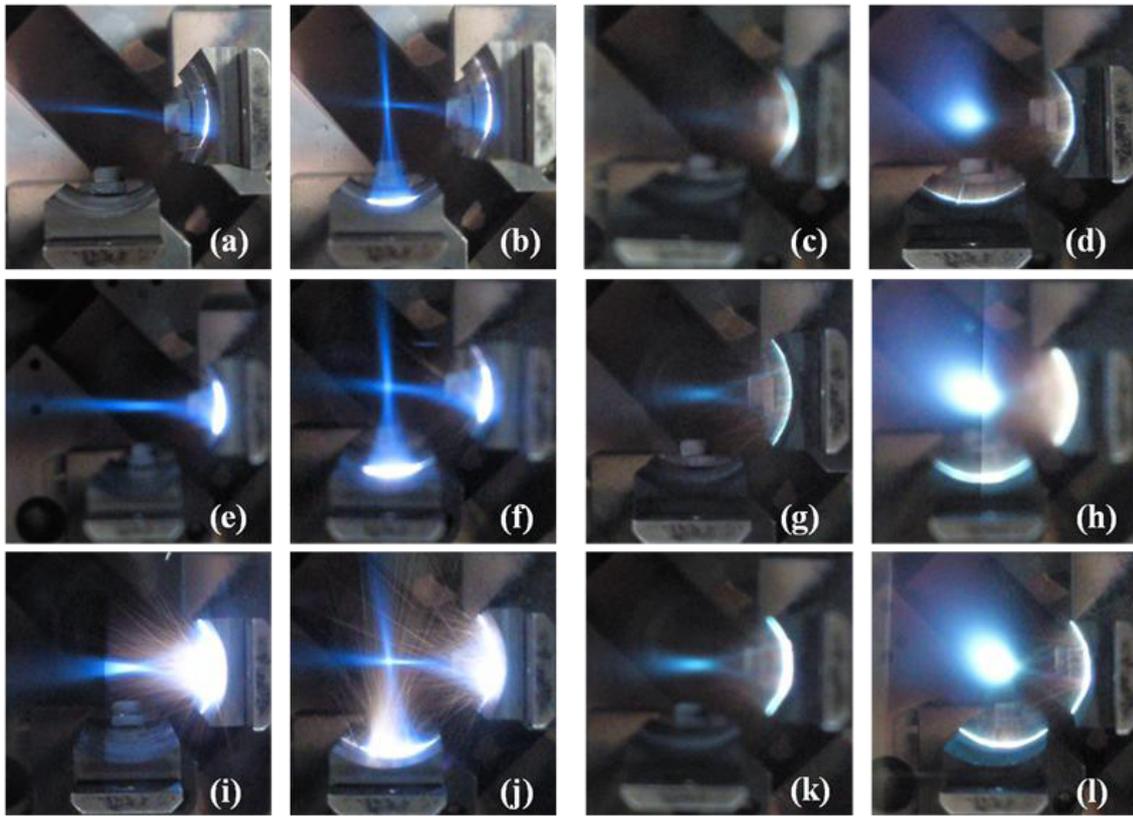


Fig. 2 Ablation plumes of tungsten (a, b) and carbon (c, d) at $2.2\text{J}/\text{cm}^2/\text{pulse}$, tungsten (e, f) and carbon (g, h) at $4.3\text{J}/\text{cm}^2/\text{pulse}$, tungsten (a, b) and carbon (c, d) at $8.7\text{J}/\text{cm}^2/\text{pulse}$, where the distance from the target surface and the center-of-arc is about 1.3cm.

to $12\text{J}/\text{cm}^2/\text{pulse}$. These targets are in the form of rectangular disk ($\sim 5\text{cm}$ by $\sim 1\text{cm}$ by $\sim 0.5\text{cm}$) but arc-shaped on the beam-facing side, and are positioned in such a way that two ablation plumes would collide with each other in the centre-of-arc region, as shown in Fig.1 (b). Used as the target materials are carbon (isotropic graphite) and tungsten (power metallurgy).

3. Results and discussion

3.1. CCD camera observations

Shown in Fig. 2 are some of the typical CCD camera images of carbon and tungsten plumes generated at 2.2, 4.3 and $8.7\text{J}/\text{cm}^2/\text{pulse}$ in the single and double target setups. Similar images to these have been observed in the laser power range examined in the present work. Notice that, due to the target curvature, all these ablation plumes focus in the center-of-arc region. In the case of tungsten, the emission tails appear to fade out after collision, compared with those seen individually. As opposed to that, carbon plumes exhibit strong emission in the centre-of-arc region due to the Swan band radiation, details of which have already been reported in our previous work [4].

3.2. Mass spectrometry

As shown in Fig.1, a quadrupole mass analyzer is

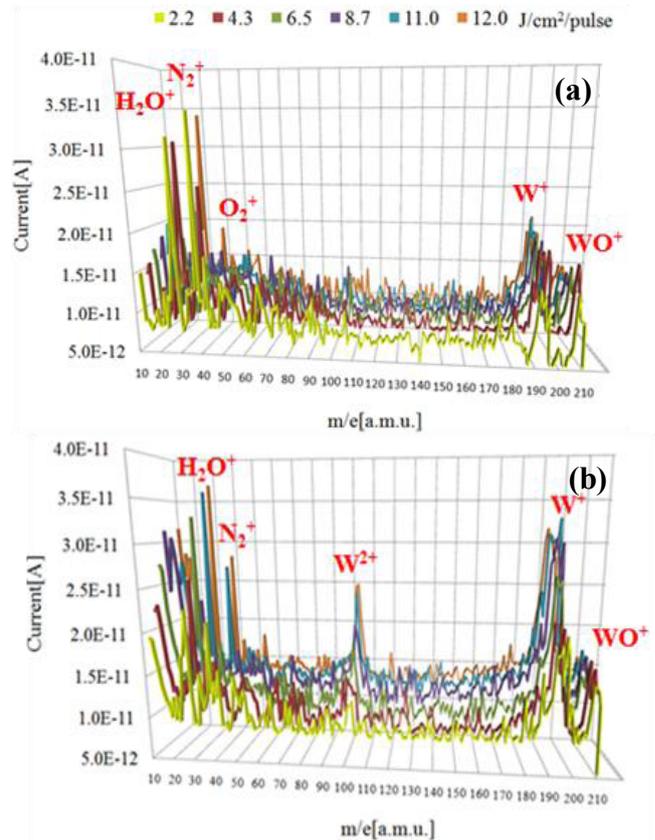


Fig. 3 Ion mass spectra of tungsten plumes generated in the (a) single and (b) double target setups at power densities between 2.2 and $12\text{J}/\text{cm}^2/\text{pulse}$.

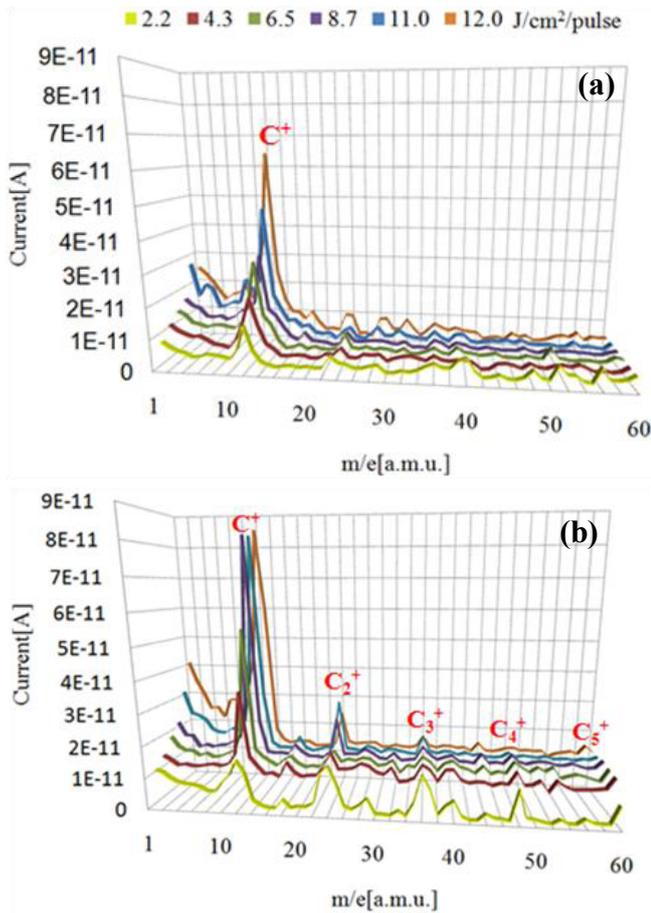


Fig. 4 Ion mass spectra of carbon plumes generated in the (a) single and (b) double target setups at power densities between 2.2 and 12J/cm²/pulse.

employed but used without hot filament in order that ions in ablation plasmas can directly be identified. The ion mass spectra taken from carbon and tungsten ablation plumes generated at power densities between 2.2 and 12J/cm²/pulse in the single and double target setups are shown in Figs.3 and 4.

It can be seen in the comparison between Figs. 3 (a) and (b), the W⁺ peak intensity observed in colliding plumes is nearly doubled, relative to that in single plumes. Interestingly, the mass spectra of colliding tungsten plumes indicate the presence of W²⁺, as shown in Fig. 3 (b), a trend similar to that observed for colliding aluminum plumes [4]. This is presumably because the electron temperature tends to increase in collision, as will be described in the following section.

Identified in common with Figs. 3 (a) and (b) are species at m/e=18, 28, and 32, respectively, suggestive of H₂O⁺, N₂⁺ and O₂⁺, again, without hot filament. Correlated to these spectra, a species at m/e=199 has been identified, corresponding to WO⁺ the mechanism of formation of which is unclear at this point.

In the case of carbon, as shown in Figs. 4 (a) and (b), only singly charged ions are identified at m/e=12, which is consistent with the ionic fraction database [5] at electron temperatures around 3eV, measured for these plumes, as described in the next section. Also, it has

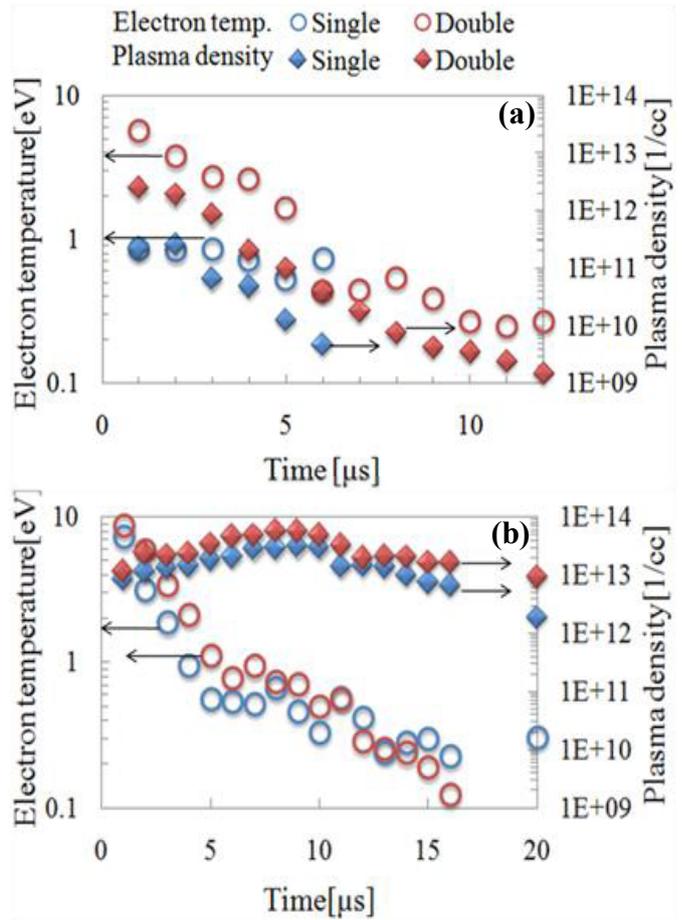


Fig. 5 Plasma parameters measured by a Langmuir probe for (a) carbon plumes and (b) tungsten plumes, all generated at 6.5J/cm²/pulse.

been found that the C⁺ intensity, i.e. plasma density, increases with increasing power density. Most importantly, carbon clusters are clearly identified in mass spectra at m/e=24, 36, 48 and 60, indicating C₂⁺, C₃⁺, C₄⁺ and C₅⁺.

It is extremely interesting to point out in Fig. 4 (b) that the cluster formation appears to favor relatively low laser power densities. This suggests that carbon cluster formation cannot simply be described by the hard sphere collision model but must be treated as an energy-dependent particle attachment reaction process, the latter of which occurs more likely at lower energies.

3.3. Langmuir probe measurements

A linearly moveable Langmuir probe is inserted into the centre-of-arc region. The plasma density and electron temperature have been measured at times after laser radiation in order that the time evolution of plasma plumes can be investigated.

Shown in Fig.5 (a) are the data taken from carbon plumes, all generated at the fixed power density of 6.5J/cm²/pulse in the single and double target setups. It has been found that the plasma density is easily doubled and the electron temperature significantly increases, both associated with plume collision. The time constants for the density decay have been evaluated to be 1.2μs and

1.4 μ s, respectively, for the single and double target setup. The slight difference between these time constants may be related to carbon cluster formation, which could then lead to the plume stagnation observed with ICCD camera [6].

In the case of tungsten, as can be seen in Fig. 5 (b), the plume plasma density is found to be nearly doubled in collision and appear to maximize before it decays, the mechanism of which is unknown, though. Also, the electron temperature is found to increase in collision. The time constants for density decay (after the maximum) have been evaluated to be 4.4 μ s and 5.3 μ s, respectively, for the single and double target setups. The difference in time constant cannot readily be explained because there is no direct proof of tungsten clusters formation due to their large mass/charge ratios. As to the decay behavior in electron temperature, observed both for carbon and tungsten, an adiabatic expansion model is currently being put together [5].

4. Summary

In the present work, to address the ICF chamber clearing issue, the first-of-a-kind demonstration has been performed, using a laboratory-scale experimental setup in which two laser ablation plumes collide with each other in vacuum. Chosen as the target materials are carbon and tungsten which are both candidate chamber wall materials. Ablation plasma plumes have been characterized by a CCD camera, mass spectrometer and Langmuir probe.

Carbon and tungsten plumes exhibit a difference in CCD camera image: the former of which shows bright emission due to collision whereas the latter of which appears to miss each other without strong interaction.

From the ion mass spectrometry, C^+ is identified in carbon plumes generated in the single target setup and its amount increases with increasing laser power density. In the double target setup, colliding carbon plumes have been found to generate cluster ions, in addition to C^+ , including C_2^+ , C_3^+ , C_4^+ and C_5^+ . Also, data indicate that the cluster ion formation favors relatively low laser power densities, indicative of inelastic atom attachment

reactions. In contrast, tungsten has exhibited W^{2+} and WO^+ along with other impurity ions, including H_2O^+ , N_2^+ and O_2^+ . Due to the instrumental limit in terms of m/e , tungsten cluster formation has not yet been confirmed despite its possibility, which clearly warrants future work in this area of research.

Ablation plume plasmas have been characterized by a Langmuir probe, changing the time delay after laser pulse. Results indicate that both the electron temperature and density decrease exponentially along with time. It has been found for both for carbon and tungsten that the time constants evaluated for density decay with plumes generated in the double target setup are generally longer than those in the single target setup, which may be related to collision-induced atomic and molecular reactions, including cluster formation.

5. Acknowledgement

The authors acknowledge the technical assistance by K. Mikami and highly appreciate fruitful discussions with Prof. Y. Sakawa and Dr. A. Sunahara.

6. References

- [1] E. Moses, "Overview and inertial confinement fusion vision", Presented at the 6th Int. Conf. on Inertial Fusion Science & Applications, San Francisco, Sep. 6th-11th, 2009 (to be published in J. Phys. Conf. Ser.).
- [2] W. Meier et al. "Integrated process modeling for the laser inertial fusion energy (LIFE) generation system", *ibid.*
- [3] K. Tomabechi et al. J. Phy. IV France 133(2006)791-795.
- [4] Y. Hirooka et al. "Laboratory experiments on cluster/aerosol formation by colliding ablation plumes", Presented at the 6th Int. Conf. on Inertial Fusion Science & Applications, San Francisco, Sep. 6th-11th, 2009 (to be published in J. Phys. Conf. Ser.).
- [5] Available at the National Institute for Fusion Science A&M-database website: <http://dpc.nifs.ac.jp/ionfracdata/> (after Amaud and Rothenflug 1985).
- [6] H. Sato, MS Thesis "Laboratory experiments on cluster/aerosol formation by colliding ablation plume" (2010), Osaka Univ.