CARBON PLUME STAGNATION: PLATFORM FOR VAPOR SHIELD STUDY

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Laser ablation scheme can cover pretty wide range of intensity regime as a heat source at its laser focus spot from 10^3 W/cm^2 to 10^{14} W/cm^2. These intensities cover the ones expected at the divertor (MFE) and the first walls (IFE) in a reactor. For example expected values are of 10 to 100 MW/m^2 at MFE divertor and 10^9 W/cm^2 or higher at IFE first walls. The ablation may include plasma, gas, liquid, or solid: all possible phases mixed at an extreme condition where temperature may exceed 1 eV with corresponding densities. The areas of these mixed phases at extreme conditions (MPEC) have not been systematically studied. The inside of the solid wall becomes so called "Warm Dense Matter" where the details of the states should still be clarified.

In our experimental setting up, the ablated plumes can be aligned orthogonally and can cross each other. The collision processes include Coulomb, elastic, molecular, and cluster collisions at the cross point. The characteristics of this experimental platform are introduced and attractive application is indicated.

I. INTRODUCTION

Around divertor targets, a high level of heat load will impinge the solid material such as Carbon, Be and Tungsten etc. Since the damage or ablation thresholds are exceeded by the incoming heat load at 10 to 100 MW/m^2 at MFE divertor and 10^9 W/cm^2 or higher at IFE first walls at plasma densities 10^{19}/m^3 or higher and temperature 1 eV through keV to MeV, some way of mitigation scheme is called for. The extreme states created in these divertor environments contain a lot of issues to be clarified such as charge states, density, sheath potential, B field etc. It is also well known that this parameter range in the solid density or above is called "Warm Dense Matter" and has been studied intensively in last decades. It has been proposed that plasma may have several active functions to mitigate the incoming heat load such as radiation cooling in "Vapor Dome",[1] chemical reaction in convective fluid,[2] sheath formation control by nano structures[3] etc. It is advantageous to establish experimental platform using lasers for this study since lasers can cover all the heat load intensities mentioned above and can create plasma plume whose density changes from solid density to vacuum. In addition that the highly temporally and spatially resolved diagnostics developed in high energy density physics can be deployed. As a result real time monitor of the heating, melting and ablation can be measured for example. In this work we introduce the experimental platform to create Carbon ablated plumes and show that the two plumes orthogonally placed intersect each other. One plume is considered to be a incoming heat flux and the other can be considered to be a plasma plume shield. The results showed that there is a plume shielding effect that is based on the molecular formation from Carbon atoms.

II. EXPERIMENTAL SETUP

Experimental set up is named "LEAF-CAP" (Laboratory Experiments on Aerosol Formation by Colliding Ablation Plumes). A third harmonic beam of YAG laser (~320mJ/pulse, 6ns, 10Hz) is optically split into equal-power and then each split beams are line-focused (~0.1mm by ~1cm) to radiate two concave targets at room temperature in a vacuum chamber (~10^{-6} Torr). Here, the line-focused area is defined by boundaries at which the laser power is attenuated to $1/e^2$. In the present work, the line-focused energy density can be varied from 2 to 12J/cm^2/pulse. These targets are in the form of rectangular disk (~5cm high by ~1cm wide by ~0.5cm thick) concave shape on the beam-facing side. Two ablated plumes from the targets collide each other in the centre-of-arc region 1.4 cm away from the target center surface, as shown in Fig.1. The target materials are carbon (isotropic graphite). The other materials can be replaced easily for further future studies.[4]

A variety of measuring tools are deployed to diagnose real-time colliding plasma plumes, including CCD/ICCD camera, qudrapole mass analyzer, visible spectrometer, Langmuir probe, and quartz crystal thickness monitor. Ablated material deposits are recovered and are observed with optical and electron microscopes. Typical set up is shown in Fig. 1 (a) and (b). Figure 1 (a) shows the third harmonic laser beams irradiates two concave targets in a vacuum chamber. Langmuir probe and mass spectrometer are placed. In Fig. 1(b), the top view of the experiment shows two concave targets are lit up with the laser irradiation. Though ablated plumes are not visible, the intersecting point lights up strongly in this time integrated photo.

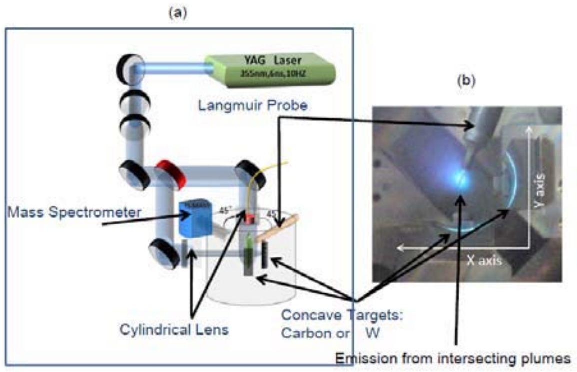

Fig. 1. Experimental Setup: "LEAF-CAP" (Laboratory Experiments on Aerosol Formation by Colliding Ablation Plumes) (a) Laser (Third harmonic YAG/~320mJ/pulse, 6ns, 10Hz) and Experimental Chamber (60 cm diameter), (b) Inside view of the LEAF-CAP. Two carbon targets of concave shape are irradiated by the two orthogonal 355 nm laser beams. The created ablation plumes intersect each other and show strong visible emission at the cross point. X & Y axes correspond to the ones in Fig. 4.

III. EXPERIMENTAL RESULTS & DISCUSSION

III.A. Characteristics of ablated plume.

When the laser irradiates a Carbon planer concave shape target, ablated plasma plume is formed. The initial temperature and density of the plume may be characterized as simulated with the hydrodynamic code. The results are shown in Fig. 2 (a) and (b) of single ablated plume for Carbon at the laser intensity 5×10^9 W/cm^2. The code was well bench-marked with EUV lithography studies where maximum efficiency of EUV light production was searched for and various solid targets were irradiated with a laser at laser intensity in our parameter range[5]. The plume at the vicinity of the target surface has a temperature 6-7 eV and density 10^{19}-10^{20} /c.c. up to 1.2 mm. The temperature distribution is rather isothermal.

Figure 3 shows the temperature and plasma density of the single ablated plume for Carbon and Tungsten measured at 1.4 cm away from the target surface. The data were measured with a Langmuir probe. As can be seen in Fig. 3, Carbon temperature ranges from 1 eV to 3 eV for laser energy density 2 to 13 J/cm2/pulse. 2J/cm^2/pulse corresponds to the laser intensity 3×10^8 W/cm^2. The plume expansion up to several cm from the target may be understood in the following way. The plasma expands isothermally first at the vicinity of the target as shown in Fig. 2 and then cools down adiabatically with the plasma density decrease with distance. However the temperature measured at 1.4 cm away from the target is a few eV. This indicates that the adiabatic cooling within the plume is only valid to some distance from the target. If we apply the adiabatic cooling all the way we will have a plume temperature much lower than the measured values at 1.4 cm. Actually hydrodynamic simulation may have some limit if the number density of the plume decreases with expansion distance. The threshold value of the hydrodynamic simulation is valid may be given when the scale length is comparable to the collisional mean free path. When the collisional mean free path exceeds the system scale length, the collision is not dominant and fluid hydrodynamic simulation may become less valid.

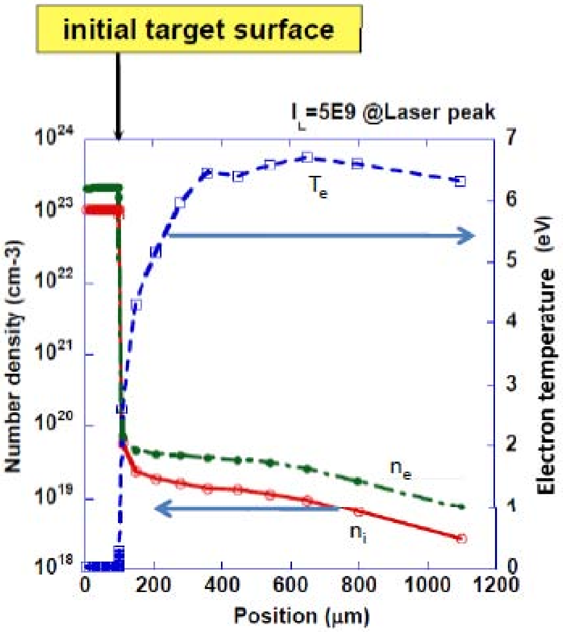

Fig. 2. Density and temperature simulated with hydrodynamic simulation of the plume at the vicinity of the target.

Below this density diffusive expansion without much collision will be dominant. The plume speed reaches 10^6 cm/sec corresponding to the plume kinetic energy 250 eV. One of the advantages in this laser based experimental platform is that we can choose the density and temperature combinations as we like. The plasma temperature distributes from 1 eV to 10 eV depending on which part of the ablated plume we choose, same for the plasma density distributing from vacuum to solid density. In this current set-up we choose to make the two Carbon ablated plumes intersecting each other at a density 10^{10} - 10^{13}/c.c. and temperature 1 - 3 eV depending on the laser energy density. One should note that the density and temperature combination is also a function of laser irradiation intensity as another freedom we can impose in this platform. This means that we can start even with 200 eV temperature with 10^{22}/c.c. initial condition.

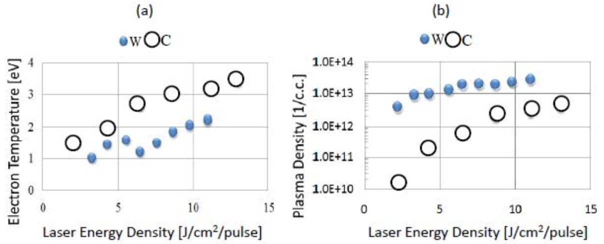

Fig. 3 Electron temperature and density of Carbon (open circle) and Tungsten (closed circle) plumes at 1.4 cm away from the target surface.

III.B. Characteristics of colliding ablation plumes

Two orthogonally oriented ablation plumes intersect at 1.4 cm away from the targets. The motion of the two plumes was measured with a fast frame intensified CCD camera. The observation frame could be shifted in time with 50 nsec time step at the camera trigger. The LEAF-CAP could be reproducible at 10 Hz. By taking many time –framed observations in the spectral range (200 -600 nm), these are put together to construct a motion movie in a X-Y plane.

In Fig. 4, we show the temporal history of Carbon plumes in X-Y plane, namely in 3D (XY-time). This has been measured with an ICCD camera with a sequence of trigger time delay by 50 nsec resulting in a movie of plume motion. It is not possible to show the motion movie in this text. The temporal series of the X-Y-plane images are piled up to compose a volume data in the XYT space (space and time). Then the multi-iso-space volume rendering is applied to obtain the final image in Fig. 4 (Ref.6). The laser energy density and intensity in Fig. 4 were 12 J/cm^2/pulse and 2 x 10^{10} W/cm^2/pulse. Two plumes came out from the line focused laser irradiated areas at speed of 10^6 cm/sec.

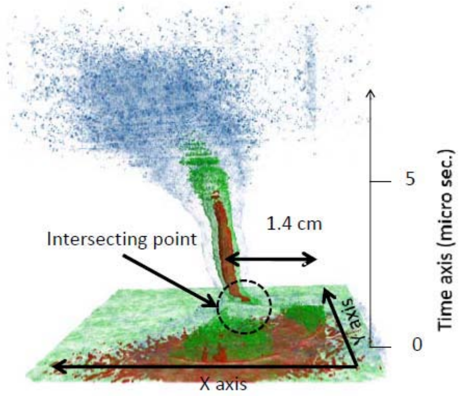

Fig. 4 Two intersecting plumes in XY and temporal axis. This volume rendered image was created from the motion movie which observed the two orthogonally oriented colliding ablation plumes.

The color of the line focused areas is shown in red (or dark shadow in black and white print(BWP)) indicating the emission of the plasma is strong at approximately 3 eV temperature. The color in the expanding plumes becomes green (or grey in BWP) indicative of cooling down to 2.7 eV. Then the two orthogonally oriented plumes show the red color again indicative of the temperature rise (3eV) at the intersection of the plumes. After 5 μsec, the stagnated and combined plume expands diffusively as shown in blue (light grey in BWP) at 2.1 eV. In addition the intersected plumes did not cross each other, nor show any transmission. On the other hand the plumes rather stagnate for about 2 μsec.

We learned that this bright emission coming from the stagnation point is due mainly from the Carbon Swan band[7] from our spectroscopic measurement This Swan band emission is the sign of Carbon molecular formation such as Carbon nano tubes etc. Then finally the stagnated cloud-like group starts moving toward the direction determined by the vector sum of the two momenta supplied by the two orthogonally oriented ablated plumes. Since the plume behaviors from for example Tungsten targets were totally different and did not show such cloud-like group formation or slow movement toward the direction determined by the momentum vector sum. The entire period of the motion happened within 8 μsec.
The residual debris was recovered from these LEAF-CAP experiments. We could find clear formation of carbon Nano and micro tubes.[8]

III.C. Plume Shielding Test

As we have mentioned in the introduction, this laser based experimental platform is aimed to study the extreme environment at around the divertor target or the first wall. We also look for any active function in plasma if it could contribute for protecting the materials at around these devices. We have tested if the ablated plume can have any protecting capability of incoming plasma flux.

We have placed a quartz thickness monitor to measure the incoming plasma plume flux at the front direction of one of the ablated plume on axis. Another ablated plume intersects this plume orthogonally at 1.4 cm away from the target irradiated with the laser beam. The density of the plasma varies from 10^{11} to 10^{12}/c.c. depending on the laser energy flux on the Carbon.

The results are shown in Fig. 5. Square plots indicate the Carbon deposition rate at the quartz thickness monitor for the incoming ablated Carbon plasma plume. The rate shows the variation up to 0.8 Å /sec.

When another ablated Carbon intersects this Carbon plume, the deposition rate of the incoming ablated plume increases from 0 only up to 0.4 Å/sec even at the highest laser energy density 7 J/cm^2 tested in this experiment. Simple estimate of the collision mean free paths for elastic and non-elastic collisions are of the order of 50 cm and 0.5 cm respectively. Namely the Coulomb collisions dominate in our intersecting area of about 1 cm diameter. We have identified there are C+ ions in the Carbon ablated plasma plumes through the mass spectrometric measurement. Also we have recovered carbon nano- and micro tubes from the deposition. We postulate at this point that the Carbon ablated plasma plumes collide each other at the intersection at temperature 1-3 eV and densities 10^{11}-$10^{12/}$c.c. in a weakly ionization state with C+ components in the plume. At the collision Coulomb collision mechanisms contributes to stop the incoming plume. Subsequently the molecular formation has started to form carbon nano tubes etc. which has been proven with the Swan band spectrum and the nano tube deposition. Even though this entire process involves complex physics processes for example molecular formation, we are planning to build a simulation capability in order to have a design capability.

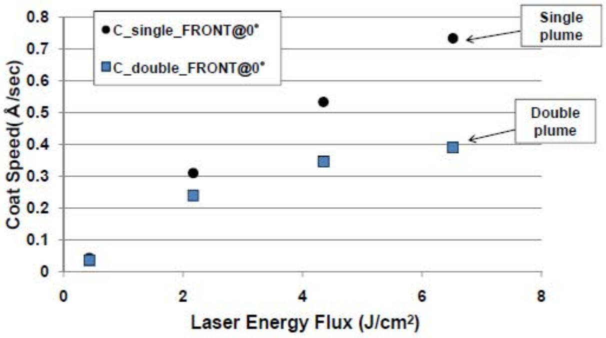

Fig. 5 Carbon deposition rate of incoming ablated plasma plume for (a) single plume and (b) single plume intersected with another plume orthogonally oriented. The ratio at these two numbers gives the transmission rate through the intersecting plume.

IV. CONCLUSIONS

We have demonstrated a laser based experimental platform which can study "LEAF-CAP" (Laboratory Experiments on Aerosol Formation by Colliding Ablation Plumes) with using Carbon targets. The characteristics of the plumes are measured. Two orthogonally oriented Carbon plumes intersect each other and show clear collision and subsequent stagnation for 2 μsec. The stagnation area emits the spectral band typical for the Carbon molecular formation. The Carbon deposits show that Carbon nano- and micro-tubes are created in this stagnated area. The transmission of incoming Carbon plasma flux is reduced up to 50 % indicating that the plasma plume has an active function to mitigate the incoming plasma flux. Using this laser based experimental platform, it will become possible to lay out magnetic field as well as ablated plasma bombardment for material ablation. In this way we show that this laser based experimental platform is a powerful tool to study the extreme environments at around the divertor and first wall in both magnetic and inertial fusion energy reactor research.

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