Laboratory experiments on the formation and recoil jet transport of aerosol by laser ablation

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Abstract. In a high-repetition rate inertial fusion reactor, the first wall will be subjected to repeated ablation along with pellet implosions, which then leads to the formation of aerosol to scatter and/or deflect laser beams for the subsequent implosion, affecting the overall reactor performance. Proposed in the present work is a method of in-situ directed transport of aerosol particles by the use of laser ablation-induced jet recoil momenta. Lithium and carbon are used as the primary ablation targets, the former of which is known to form aerosol in the form of droplet, and the latter of which tends to form carbon nanotubes. Laboratory-scale experiments have been conducted to irradiate airborne aerosol particles with high-intensity laser to produce ablation-induced jet. Data have indicated a change in aerosol flow direction, but only in the case of lithium.

1. Introduction
Along with repeated pellet implosions, the interior surface structures of the target chamber of a high-repetition rate inertial fusion reactor are exposed to short pulses of high-energy x-ray, unburned DT-fuel particles, He-ash and pellet debris. As a result, surface materials are subjected to ablation, emitting particles in the plasma state. Ablated plasma particles will either be re-deposited elsewhere on the wall or collide with each other, perhaps in the centre-of-symmetry region of the chamber volume. Colliding ablation plasma particles can lead to the formation of molecular clusters to grow into aerosol, possibly floating thereafter, which can then deteriorate the subsequent implosion performance via laser scattering, etc. Clearly, this points to a need for the in-situ removal or displacement of aerosol from the position of ignition. Proposed in the present work is a method of directed transport of aerosol particles by the use of laser ablation-induced jet recoil momenta.

2. Experimental
Employed in our previous studies is a laboratory-scale laser ablation experiment setup, referred to as LEAF-CAP for the Laboratory Experiments for Aerosol Formation by Colliding Ablation Plumes [1]. Used for the primary ablation process in the LEAF-CAP setup is a 1 Joule YAG laser beam (3rd harmonic), which is first split into two equal power beams, both line-focused down to 1cm x 0.01cm, irradiating two arc-shaped targets at 10Hz, each 6ns long, so that the energy density ranges from 3 to
10 J/cm$^2$/pulse. These two targets are set in vacuum, positioned in such a way that ablation plasma plumes will collide with each other in the center-of-arc (CoA) region, as shown in figure 1.

In our recent work, colliding ablation plumes from graphite have been found to generate aerosol in the form of carbon allotropes such as carbon nano-tubes [2], whereas those from metals tend to form aerosol in the form of droplets [3]. In both of these cases, aerosol particles have been observed to flow in the compound velocity direction of the colliding plumes, apparently cancelling the momenta in the counter directions and to be deposited eventually on the sampling plate.

In the present work, the LEAF-CAP setup has been modified with an additional 250m Joule YAG laser beam (2$^\text{nd}$ harmonic), line-focused in the two directions, i.e. horizontal and vertical, to intersect the flow of aerosol at around 5mm away from the CoA-region at 10Hz, each 8ns long, as illustrated in figure 1. The energy density in this laser beam is set typically at 3.3J/cm$^2$/pulse. Also, a quartz crystal film thickness monitor is employed, set at the position of the sampling plate, so that the arrival rate of aerosol can be monitored in real-time during the double-action laser ablation process. One can then expect to see a decrease in molecular arrival rate when the redirection of aerosol occurs as a result of the ablation by 2$\omega$-YAG laser irradiation. In parallel with aerosol arrival rate monitoring, visible spectroscopic measurements are conducted, viewing the region where the aerosol flow is intersected by the 2$\omega$-YAG laser beam. In a separate experimental setup, where the film thickness monitor is removed, ion charge collector measurements have also been conducted.

3. Results and discussion

3.1. Visible spectroscopy measurements
Shown in figure 2 is the streaking light observed by an ICCD camera along with the vertically line-focused 2$\omega$-YAG laser beam, intersecting a carbon aerosol flow generated from two carbon targets. Visible spectroscopic analysis has been done on this streaking light, and the data are shown in figure 3. Recognize the Swan band is observed, before 2$\omega$-YAG laser irradiation, indicating the formation of C$_2$ molecules although it is partially covered (520nm–540nm) by the filter. As can be seen in figure 3, with 2$\omega$-YAG laser irradiation, the swan band spectra are superimposed with line emissions from C$^+$, C$^{+1}$ and C$^{+2}$ which are believed to be generated by the decomposition of carbon aerosol.

Unlike carbon, lithium does not appear to exhibit any observable streak lines with the irradiation of 2$\omega$-YAG laser beam, line-focused in either direction. As shown in figure 4, however, visible spectroscopy data indicate a significant increase in Li-I line intensities, all of which are related to neutral species, under identical conditions to those employed in the case of carbon.
3.2. Ion charge collector measurements
In addition to visible spectroscopy, a charge collector has also been used to detect the effect of the irradiation of 2ω-YAG laser. This charge collector is composed of an ion collector covered with a mesh and an isolated chassis. During its operation, the ion collector is DC-biased to -10V and the mesh and chassis are at the same floating voltage. Generally, it is known for this type of ion charge collectors that a sharp increase in signal is observed after a temporal indication of a negative current due to electrons arriving at the collector [4].

Shown in figure 5 are the results from ion current measurements on lithium ablation plasmas with and without 2ω-YAG laser irradiation, both indicating the general trend described above. With a few micro second of delay, a sharp increase in ion current has been observed, presumably due to an increase in plasma density by the 2ω-YAG laser irradiation which, however, is not indicated by the visible spectroscopy data shown in figure 4. From these data, the plasma (ion) density has been estimated to be of the order of $10^{10}$ m$^{-3}$ at the position where the charge collector is placed.

3.3. Aerosol arrival rate measurements
In the case of carbon, no clear sign of ablation-induced jet effects has been identified in the aerosol arrival rate monitoring data. This may be due to the decomposition of carbon aerosol being rather isotropic or due to the insufficient energy density of 2ω-YAG laser irradiation. Consistently with this, in our previous work, carbon has been found to be most difficult to generate high-density ablation plasmas, compared with the other materials examined [2].

In the case of lithium, as shown in figures 6-(a) and (b), noticeable changes in molecular arrival rate have reproducibly been seen with the irradiation of 2ω-YAG laser beam, even as there is intrinsic fluctuation and/or noise in the arrival rate monitoring signal. In the case of vertically line-focused irradiation, the energy density of 2ω-YAG laser is particularly raised to 12J/cm$^2$/pulse so as to enhance the effect of ablation-induced jet.

Two possibilities have been investigated to interpret these observations: (1) First, the radiation pressure, induced by the 2ω-YAG laser irradiation is evaluated, using the model for laser driven ablative implosions [5]. The result indicates that the 2ω-YAG laser used in the present work is not strong enough to redirect the flow of aerosol.

![Figure 3](image3.png) Visible spectroscopy of the carbon aerosol with and without 2ω-YAG laser beam irradiation. Data with 2ω-YAG laser beam irradiation are taken from the streak light shown in figure 2.

![Figure 4](image4.png) Visible spectroscopy of the lithium aerosol with and without 2ω-YAG laser beam irradiation.

![Figure 5](image5.png) Charge collector measurements of lithium ablation plasma with and without 2ω-YAG laser beam irradiation.
(2) Next, the effect of laser ablation-induced jet recoil is evaluated, assuming that lithium aerosol particles are spherical and for simplicity, only the hemisphere irradiated by 2ω-YAG laser is heated up although, in actuality, the entire body temperature increases. The velocity of aerosol powered by ablation-induced jet is found to be inversely proportional to the diameter. Importantly, the velocity must be below a certain level to be detected by the film thickness monitor with a sensor diameter of only 8mm. This simple ablation-induced jet model then predicts that only the aerosol particles with diameters larger than ~7μm could arrive at the sensor. As can be seen in figure 7, however, the number density of lithium aerosol particles satisfying this diameter requirement is not large, which is believed to have led to the difficulty in arrival rate measurements.

Figure 6 Lithium aerosol arrival rate data, measured by a quartz crystal film thickness monitor, with and without 2ω-YAG laser beam irradiation: (a) vertically line-focused and (b) horizontally line-focused. Irradiation periods of 2ω-YAG laser are indicated by the yellow-highlighted zones.

Figure 7 Lithium aerosol deposited on a pyrex glass sampling plate placed in the quartz crystal film thickness monitor [3].

4. Conclusion
In the present work, the possibility of applications of ablation jet momenta has been addressed for the directed transport of aerosol particles that are predicted to be formed in the pellet implosion region in a high-repetition rate inertial confinement reactor.

A series of laboratory-scale experiments have been conducted in which two consecutive laser ablation processes take place, the first one of which generates aerosol particles via laser ablation, and the second of which is intended to provide recoil jet momenta to re-direct the flow of airborne particles. Carbon and lithium are chosen as the primary ablation target materials.

Data from these experiments have indicated a change in aerosol flow direction when the secondary laser ablation takes place, but only in the case of lithium. Clearly, further effort is necessary to understand more details on the dynamics of aerosol transport and its redirection. Nonetheless, the present work has opened the door to a new area of research, contributing to the achievement of inertial fusion energy, or at least so we believe...

References
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