Dynamics of laser produced annular plasmas

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Abstract. We present preliminary experimental observations of the plasma dynamics of laser produced annular plasmas, expanding freely in a 80 mTorr Argon background. A Nd:YAG laser, 340 mJ, 3.5 ns, at 1.06 \( \mu \)m, operating at 10 Hz, is used in the experiments. To produce the annular plasma the laser pulse is focused on a titanium target using a combination of axicon and convergent lens. The dynamics of the laser plasma is characterized by 50 ns time resolved plasma imaging of the visible plasma emission. The inwards radial expansion of the initial plasma ring result in on-axis stagnation, giving rise to an expanding axial laser plasma plume. A quantitative description of the laser plasma dynamics is presented.

1. Introduction
An annular plasma can be produced by focusing a collimated laser beam over a flat solid target, using a combination of axicon prism and convergent lens \cite{1}. These ring-like plasmas have been used to initiate an annular gas-embedded z-pinch \cite{2} or to enhance plasma emission in laser induced breakdown spectroscopy (LIBS) \cite{3,4}, among other applications. Here we present preliminary results on the study of the plasma dynamics, both radial and axial, of a laser produced annular plasma.

2. Experimental set-up
In the experiments we use a Nd:YAG laser, 340 mJ, 3.5 ns, at 1.06 \( \mu \)m, operating at 10 Hz. The laser beam is focused over a flat Titanium target, using a combination of axicon and focusing lens, which produces an initial plasma ring of 5 mm radius and 200 \( \mu \)m thickness. Laser power density on target was \( 1.6 \times 10^9 \) W/cm\(^2\). In order to be able to compare with point focus laser produced plasmas studied before \cite{5}, the experiments were conducted in Argon background, at 80 mTorr. The laser plasma is characterized by 50 ns time resolved plasma imaging of the visible plasma emission using an Andor ICCD camera. The laser produced plasma expands either freely. A schematic of the experimental set-up is presented in figure 1.

3. Results and discussion
Figure 2-a shows images of the initial stages of the laser annular plasma. At \( t = 34 \) ns the plasma is localized close to the target surface, on the left hand side of the image. The shape corresponds to the emission that of a rather uniform annular plasma, of \( \sim 5 \) mm radius. The onset of an
Figure 1. Experimental set-up: a) Laser beam, b) Axicon prism, c) Focusing lens, d) Titanium target, e) Annular focused laser beam, f) Laser produced annular plasma, g) Light collecting assembly for plasma imaging.

The axially expanding laser plasma plume is also observed, which is due to stagnation on axis of the initial annular laser produced plasma [1]. At $t = 74$ ns the plasma is already expanding axially, being the dominant feature the expanding plasma plume resulting from on-axis stagnation. This is observed clearly in the radial profile of the light intensity at 2.5 mm from the target surface, shown in figure 2-b. Here it can also be appreciated that at this time the radial profile of light intensity is not symmetrical, which can be explained due to small misalignments in the optical system and/or inhomogeneities of the laser beam.

Figure 2. a) Plasma images showing the initial stages of the annular plasma evolution, and b) Radial profile of the light intensity in the same images, at 2.5 mm from the target surface.

Figure 3 shows the time evolution of the laser produced plasma. For times up to 340 ns, the distinctive feature of the laser produced plasma is that of an axially expanding plasma jet, with a characteristic bow-like, wider plasma front at the leading edge. This can be explained in terms of a combination of a tight axial expanding plume resulting from on-axis stagnation of the initial annular plasma ring, and the axial displacement of the disk-shaped initial plasma. At later times the axial plasma jet is seen to decay, being the dynamics dominated by the expansion, both axial and radial, of the bow-like initial plasma front. In particular, the plasma is seen to decay by expansion and cooling in a time scale of $\sim 4 \mu$s.

In order to characterize the plasma dynamics we plotted the radial and axial positions of the leading plasma front, defined by the light emitting edge of the plasma, as a function of time. This is shown in figures 4-a and 4-b, respectively. The radial expansion was measured at 2.5 mm from the target surface. The initial annular plasma is seen to expand radially with constant velocity $1.2 \cdot 10^4$ m/s. This is shown by the linear fitting in figure 4-a. In contrast with the radial dynamics, the axial expansion of the plasma does not show a constant velocity feature. This can be described quantitatively by the drag model [6–8]. During the expansion process the plasma is not subject to energy input, so the later dynamics is determined by the energy released on target at plasma creation. At later times, and in the presence of a neutral background gas, the expanding laser plasma drags background gas, which results in and increasing mass load at the expanding plasma boundary, leading to an eventual stop. In this case the expansion...
dynamics as a function of time is given by

$$ z(t) = z_s \left( 1 - e^{-\beta t} \right) - z_0 $$

where $z_s$ is the stopping distance, $\beta$ is the dragging coefficient, and $z_0$ is an initial condition that allows a delayed onset of the plasma plume emission, as compared with the time of initial laser plasma formation. From Eq. 1, the initial velocity of the plasma front is $v_0 = \beta z_s$. In this case, the application of the drag model leads to the solid fitted lines in figure 4-b. It can be inferred that the drag model describes well the axial dynamics of the plasma. Details of the drag model fitted parameters are presented in table 1.

In general, the stopping distance $z_s$ is determined mainly by the presence of the background gas. The adjustment parameter $z_0$ is mainly determined by the time interval required for light emission to take place, following the creation of excited state in the laser plasma at $z = 0$ [7]. This time interval depends on the laser power density and target material. The initial axial
velocity, $v_0$, results to be almost twice that of the constant radial velocity. This is due to the fact that the initial axial velocity is determined by the explosive behavior of the initial laser produced plasma, whereas the radial velocity is determined mainly by the thermal expansion of the plasma in a low pressure background, which does not experience dragging effects on the spatial scale involved in the experiments. In general, the plasma images in figure 3, at later times, show a distinctive behavior, qualitatively similar to that of the single focal point laser produced plasma, expanding in a neutral gas background [5–8].

4. Conclusions
We have performed preliminary experiments to characterize the plasma dynamics of laser produced annular plasmas. A point to highlight is the observation of on-axis stagnation, which leads to the formation of a jet-like plasma. Further experiments, with additional diagnostics and different parameter regimes for the formation of the laser produced annular plasma are being performed, which will be reported elsewhere.

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References
[1] Veloso F, Chuaqui H, Aliaga-Rossel R, Favre M, Mitchell I H, and Wyndham E 2006 Rev. Sci. Instrum. 77, 063506
[2] Veloso F, Chuaqui H, Correa N, Favre M, and Wyndham E 2009 Plasma Sources Sci. Technol. 18, 045013
[3] Cabalín L M and Laserna J J 2004 J. Anal. At. Spectrom. 19, 445
[4] Malevich P N and Chumakov A N 2012 J. Appl. Spectroscopy 79, 838
[5] Ruiz H M, Guzmán F, Favre M, Bhuyan H, Chuaqui H and Wyndham E S 2012 Plasma Sources Sci. Technol. 21 034014
[6] Geohegan D B 1992 Appl. Phys. Lett. 60 2732
[7] Gonzalo J, Afonso C N, and Madariaga I 1997 J. Appl. Phys. 81, 951
[8] Harilal S S, Bindhu C V, Tillack M S, Najmabadi F, and Gaeris A C 2003 J. Appl. Phys. 93, 2380

| Fitting parameters | $z_s$ (mm) | $\beta$ (s$^{-1}$) | $z_0$ (mm) | $v_0$ (m/s) |
|--------------------|------------|-------------------|------------|-------------|
|                    | 37.8       | 5.67 $\cdot$ 10$^{-4}$ | -5.7       | 2.15 $\cdot$ 10$^4$ |

Table 1. Drag model adjusting parameters