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Confinement and re-expansion of laser induced plasma in transverse magnetic field: Dynamical behaviour and geometrical aspect of expanding plume

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ABSTRACT

We present dynamical behaviour of aluminium plasma across 0.45 T magnetic field at low ambient pressure using fast imaging technique. The present finding related to the plume dynamics, splitting pattern and geometry of plume is significantly different from reported results on similar experiments. In vacuum, after the initial expansion, the plume is tending to stagnation and begins to re-expand with constant velocity. The above behaviour is correlated with the plume expansion in diamagnetic limit and $E \times B$ drift in non-diamagnetic regime. Two slab like structures, moving with different velocities are observed in presence of both the magnetic field and ambient gas.

1. Introduction

The presence of magnetic field during the expansion of laser-blow off (LBO)/laser produced plasma (LPP) can initiate several interesting physical phenomena, which include conversion of kinetic energy into plasma thermal energy, plume confinement, ion acceleration/deceleration, emission enhancement/decrease and plasma instabilities [1–8]. The physics of plasma flow across magnetic field lines is important in many laboratory, tokamak and space plasmas and has significant importance in many applied researches, for example, increase in the detection sensitivity of laser-induced breakdown spectroscopy [1,9], manipulation of plasma plume in pulse laser deposition [10–12], debris mitigation etc. [13]. Also several pioneer works related to the basic understanding of plasma plume–magnetic field interactions have been done with regard to the formation of diamagnetic cavity and flute like structures [14–16], plasma oscillations [17], edge instability and dramatic structuring [18,19], sub-Alfvenic plasma expansion [20] and laser plasma expansion in magnetized background [21].

Apart from the above, dynamics of plasma plume is influenced significantly in the presence of the magnetic field and therefore it is useful to control the dynamic properties of highly transient plasma plume. The manipulation of geometrical shape, size and dynamics of plasma plume by introduction of external magnetic field has great importance in applied research and also in fundamental studies. Due to initial conversion of thermal energy into directed energy at the initial stage of laser produced plasma, sum of directed pressure and thermal pressure of plasma plume is much larger than the magnetic pressure (that is plasma beta >1). As the time evolves, electron temperature and density of the plasma plume decrease rapidly as a result plasma beta is also decreases with time. Therefore, two different approaches have been made to explain the dynamics of laser produced plasma across the transverse magnetic field. In the first approach expansion of the plasma plume is treated as expansion in the diamagnetic limit where the applied electric field is displaced by the induced field due to diamagnetic current in plasma and the plasma plume experiences the decelerating force [2,8,14]. In the second approach, it is considered that external magnetic field is diffused in the plasma plume and produces polarized electric filed (due to the deflection of electrons and ions in opposite direction) perpendicular to both the expansion direction and the magnetic field [8,22,23]. In this case plasma plume experiences the $E \times B$ field and drifts in axial direction. In most of the previous experiments with ns laser and moderate laser energy (up to few hundred mJ), the dynamics of plasma plume across the magnetic field is explained in terms of $J \times B$ interaction induced by diamagnetic behaviour of plasma plume [2,4,9]. Drift of the bulk plasma across the magnetic field and field aligned insta-

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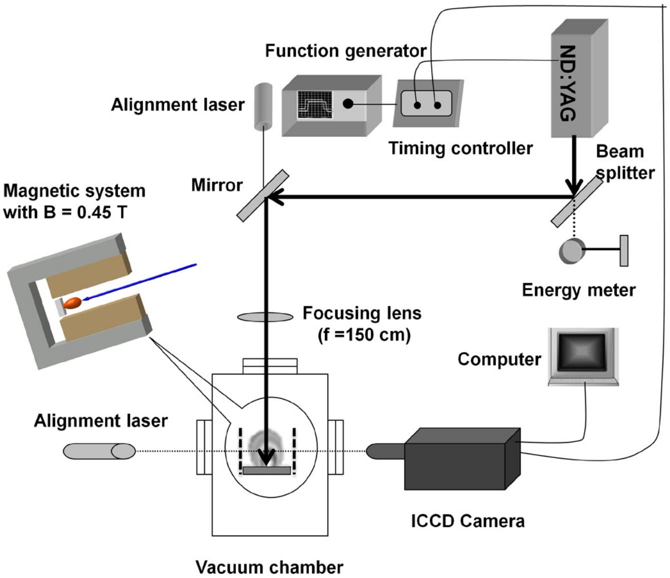

Fig. 1. Schematic of the experimental set-up.

bility (striation like structure) is commonly ignored, especially for moderate laser energy.

In view of above, in the present work we report a systematic study of the effect of the magnetic field regarding the dynamical and geometrical behaviour of laser induced plasma plume in different ambient conditions. We attempt to demonstrate the expansion of transient plasma plume in diamagnetic limit followed by drift across the polarized electric field.

2. Experimental scheme

Schematic diagram of the experimental setup is shown in Fig. 1. The plasma plume is created in a cylindrical stainless steel chamber, which is evacuated to a base pressure less than 2×10^{-5} Torr. A uniform magnetic trap was made by two rectangular Nd–Fe–B permanent magnets having dimensions 38 mm height, 76 mm length and 76 mm width. A non-magnetic stainless steel structure holds the magnets parallel to each other with 30 mm separation, which produces ∼0.45 T uniform magnetic field. Magnitude and uniformity of the magnetic field is ensured by mapping the magnetic field along the expansion and lateral directions using Gauss meter. The aluminium target was mounted on a movable target holder through a vacuum compatible feed-through and placed in between the two magnet bars. An Nd:YAG ($\lambda = 1064$ Å) laser having 8-ns pulse width with pulse energy 300 mJ has been used to ablate the target. The spot size of the laser beam is set to about 1 mm in diameter at the target which can produce the power density $\sim 4 \times 10^9$ W/cm^2 the target surface.

The light emitted from the luminous plasma is transmitted though a quartz window mounted orthogonal to the direction of the plume expansion. Time resolved images of the visible plume luminescence have been recorded using an ICCD camera having variable gain and gating on time and having a spectral range of 350–750 nm. In the present experiment, gate opening (integration) time is set at 10 and 20 ns. Temporal evolution of the laser produced plume has been obtained by varying the time delay (from 400 to 5000 ns) between the laser pulse and the opening time of ICCD gate. Minimum three images are recorded under similar experimental conditions. The reproducibility of the emission intensity is better than 5%. A mesh image of known dimensions (5 mm × 5 mm) is recorded to map the geometrical parameters of the plume. The magnification of the imaging system is found to be 3. Dark current noise is subtracted from the recorded image using MATLAB. Length and width of the plume are estimated by segmentation algorithm using MATLAB. For better visibility, grey images have been converted into pseudo-colour images using jet-colour map. A micro-controller based time control unit is used to trigger the camera in synchronous with the laser pulse. Timing jitter in time delay with respect to laser pulse is less <1 ns. To find the emission profile along the axial as well as lateral directions, plume images are binned along the horizontal and vertical columns of images respectively.

3. Results and discussions

In order to understand the hydrodynamic movement of the expanding aluminium plasma in presence of strong transverse magnetic field, the images of the emitting plume are recorded by the ICCD camera for different ambient conditions. These images provide temporally resolved two-dimensional snapshots of the expanding laser produced plasma plume. Here it should be noted that for the present experimental configuration, it is possible the expanding plasma plume touches the magnet surface at higher delay time. The plasma–magnet interaction and its effect on plume dynamics is complex phenomenon and it is subject of separate investigation. However the separation between the two magnets is considerably large (30 mm) and therefore the lateral physical obstacle may not affect significantly the characteristic dynamics of the plume in axial direction. Since, the present work basically focused on axial dynamics of plume and hence the plume–magnet interaction is ignored in this report.

The effect of magnetic field as well as ambient condition on the dynamics and geometrical shape of the expanding aluminium plasma are studied by observing these emissions as a function of time. Fig. 2 shows the sequence of images recorded at different time delays, varying from 400 ns to 5000 ns in vacuum and in the presence of 0.45 T magnetic field. Each image represents the spectrally integrated emission intensity in the range 350–750 nm emitted from plume species. For better presentation of emission intensity distribution in the plasma plume and its temporal variation in the axial direction, the integrated intensity profile along the expansion axis for each image is also included in Fig. 2. As can be seen from Fig. 2, geometrical shape and intensity distribution of the plasma plume is significantly different from the previously reported results. Up to the 400 ns, plume expands under the influence of directed pressure (due to the large pressure gradient) and has an ellipsoidal shape. The presence of resistive force due to the magnetic pressure is clearly observed at 400 ns where the front is compressed and its shape is deviating from the ellipsoidal structure. At $t = 800$ ns, well defined intensity columns parallel to the magnetic field line are observed ahead of bulk plume. This striation like structure is clearly observed from 800 ns to 1400 ns. Similar structure has been reported in past with much larger laser energy as compared to the present case [8] where, it is attributed as velocity sheer induced instability. At the present stage it is not clear whether the plasma instabilities or plume–magnet interaction are responsible for observed striation. Detailed investigation of this aspect will be reported in future communication. As the time evolves bulk plume starts moving towards the magnetic pole whereas axial expansion is still negligible up to $t = 1200$ ns. As a result, plume becomes more elongated in lateral direction with the time delay. With further increase in time delay $t > 1200$ ns, the elongated plume starts moving in axial direction but the polarization of plume species near the magnetic poles goes on. At time delay $t > 3500$ ns, intensity of the central portion of the plume starts decreasing and the overall structure look like a plume splitting in the vertical direction. Here it is noted that illumination of magnet boundary is mainly due to the light reflection and polarization of plume species near to magnet surface. For the present