Effect of magnetic field on the laterally colliding plasma plumes

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An experimental investigation of laser produced colliding plasma of aluminium target in the presence of external magnetic field in vacuum is done. Characteristic parameters and line emission of plasma plume in the presence of magnetic field are compared with those for field free case. Axial expansion of the plasma is slowed down in the presence of magnetic field as compared to the field free case. Contrary to the field free case no sharp interaction zone is observed. Higher electron temperature and increased ionic line emission from singly as well as doubly ionized aluminium can be attributed to the Joule heating phenomenon.

I. INTRODUCTION

Collision of plasma plumes is an important phenomenon in many laboratory plasma and applications such as plasma confinement, inertial confinement fusion (ICF), laboratory studies of plasma of astrophysical importance, generation of nanoparticles and ion-sources etc. [1–6] Expansion of laser produced plasma in the presence of an external magnetic field has been studied experimentally under different conditions and has been illustrated in recent works. [1, 7–10] Colliding plasma with different targets, laser parameters, ambient and ablation geometries have been reported by several authors. [11–24] In our earlier work in aluminium colliding plasma we had found a clear distinct interaction zone and neutral emission is significantly enhanced at later times due to increase in three body recombination. [25]

Plasma-plasma interaction in the presence of external magnetic field is an interesting phenomenon to study because of its implications from the understanding fundamental physics as well as applications. Effect of magnetic field on the colliding plasma is quite interesting from the view point of its ramification in the plasmas of astrophysical importance to the technological aspect. To the the best of our knowledge, study regarding the colliding plasma in the presence of an external magnetic field has not been attempted so far. Therefore, in the present work we tried to explore the colliding plasma phenomenon in the presence of an external varying magnetic field by using fast imaging and optical emission spectroscopy (OES).

II. EXPERIMENTAL SETUP

A schematic diagram of the experimental setup is shown in Fig. 1. A specially designed Helmholtz coil which can produce a transverse magnetic field varying from 0 to 6000 Gauss is placed inside a vacuum chamber. The coil has dimension of $5 \times 5 \times 5$ cm$^3$ and a flat-top magnetic profile which can be operated from outside without disturbing vacuum inside the chamber. Experiment is done in vacuum i.e. $5 \times 10^{-7}$ mbar. Detailed experimental discussions on experimental setup are given elsewhere. [25] Briefly, laser beam of an Nd:YAG laser ($\lambda = 1064$ nm, pulse width $\sim 8$ ns, full-width at half-maximum) has been split into two beams of 100 mJ each. These two beams are focused by a plano-convex lens (35 cm focal length) on a clean aluminium target surface (99.9% purity). The target dimensions are $6 \times 3 \times 1$ cm$^3$ and is placed at the central region of the coil by using a vacuum compatible feed-through. The target positions are changed by 2 mm to a fresh surface after each consecutive 5 shots by using the linear scale on the feed-through. The experiment is done in single shot mode. The spot size and separation between the two beams are set as 1 mm and 4 mm, respectively. Magnetic field, ICCD camera, spectrograph and laser are synchronized with the combination of function generator and delay generator with jitter $\sim 1$ ns.
III. RESULTS AND DISCUSSION

A. Fast Imaging

Figure 2(a) shows temporal evolution of the laser produced single plasma plume in field free case and in the presence of magnetic field. All the images in this article are line integrated images in wavelength range of 350 to 700 nm and normalized to maximum intensity. The expansion of plasma without external field is free, adiabatic and its luminosity is beyond the detection limit at t>1000 ns. However, expansion dynamics and characteristics of the plasma changes with the introduction of transverse magnetic field. The major differences observed from these images are as follows. At shorter times i.e. from 100 to 300 ns delay times the axial expansion velocity i.e. velocity perpendicular to the target surface, increases and then decreases at later time delays. This phenomenon has been attributed to plasma oscillations due to diamagnetic effect.[1][26] After 300 ns, free expansion of the plasma plume in axial direction appears to be slowed down by the resistive force induced by external magnetic field. On the other hand, plasma plume does not experience any resistive force along the field lines and therefore plume expands freely along the magnetic poles. A well resolved striation along the field lines is observed in presence of field, which is more pronounce at high field intensity and later stage of plasma. Striation phenomenon has been studied by many authors in earlier works.[1][27] Another important feature observed in the presence of magnetic field is increase in emission intensity of the plasma (the luminosity of the plasma plume persists up to few microseconds). This is also supported by spectral data which will be discussed latter.

Effect of magnetic field on laser produced single plasma is well studied.[1][3][6] In the present study we focus on the study of interaction zone formed by colliding plasmas in presence of external magnetic field. Figure 2(b) represents time integrated images of lateral interactions of two spatially separated plasma plumes in absence and presence of 1000 Gauss magnetic field, respectively, for time delays 100 to 600 ns in vacuum. In the absence of magnetic field, a well formed interaction zone is observed at the centre of interacting plumes which is moving with higher velocity in comparison to the seed plumes. Interestingly the shape, size, geometry of the colliding plasma and the subsequent interaction zone exhibit drastic changes with the introduction of magnetic field. It can be seen from this figure that no clearly separated interaction zone is present in the presence of the field in contrast to field free case. Although overlap appears to be there between the transversely elongated plumes in presence of magnetic field. These changes can be understood as follows. Collisionality parameter \( \zeta = D/\lambda_{ii} \), defines the nature of induced interaction zone in a colliding plasma plumes, where D is separation between two laser beams and \( \lambda_{ii} = [(m_i^2v_i^2)/(4\pi e^4Z_i^4n_i\ln\Lambda_{i2})] \) is ion-ion mean free path.[28] Here, \( m_i \), \( v_i \), \( Z_i \), \( n_i \) and \( \Lambda_{i2} \) are the ion mass, relative velocity of two plumes, ionization state, plasma density and Coulomb logarithm of the plasma. The estimated collisionality parameters are \( \zeta = 5 \) and 10 for B = 0 and 1000 Gauss, respectively. These values predict soft stagnation for both the cases. However, in the presence of magnetic field, the ion-ion mean free path is likely to be modified because of ion gyration and hence can affect the estimated parameters. In this scenario the collisionality parameter may not represent the true picture of interaction region in the presence of the field. This can be understood by the Larmor radii. Larmor radii are calculated from \( mv_i\perp/qB \), where \( m, v_i, q \) and \( B \) are mass of the charged particle, velocity perpendicular to the field, charge and magnetic field, respectively. Estimated values for electron, Al\(^{+} \) and Al\(^{2+} \) Larmor radii are 3 \( \mu \)m, 7 cm and 14 cm, respectively. The Larmor radii for ions are bigger than the plume dimension. Larger Larmor radii for the both Al\(^{+} \) and Al\(^{2+} \) may decrease the ion-ion collisions which may result in the absence of clear interaction zone in magnetic field.

In presence of magnetic field, the value of \( \beta \) plays important role in governing the expansion dynamics of the plume. Thermal beta is expressed by the ratio of thermal pressure and magnetic pressure i.e. \( \beta_i = n_iT_i/B^2/2\mu_i \), where all notations have their standard meanings. The expansion of the plasma plume transverse to the magnetic field stops, when thermal beta becomes equal to one i.e. thermal pressure of plasma is equal to magnetic pressure. For the present experimental condition, the estimated value of thermal beta is around unity at 500 ns delay. However, plasma plume does not stop at 500 ns rather.
it is slowed down as can be seen from Fig. 2(a) and 2(b). This is because in laser produced plasma, thermal energy is converted into directed energy and hence directed beta becomes important. The plasma expansion beyond the region $\beta_r \approx 1$, can be attributed to the directed beta \( \beta_d = \left( \frac{m_e v^2}{2 B^2/\mu_0} \right) \) of the plasma which is always greater than unity for the considered time delay.

Another important parameter is bubble radius which is described by $R_b = [(3\mu_0 E_{pp})/(2\pi B^2)]^{1/3}$ for a spherical plasma plume expanding in magnetic field. Where, $\mu_0 = 4\pi \times 10^7 \text{ H/m}$, $E_{pp}$ is laser energy and $B$ is the external magnetic field. The bubble radius, estimated from this equation is 1.77 cm for $B = 1000$ Gauss, which is comparable to our plume dimension of 2 cm as observed in images. The small difference observed in this case can be attributed to the assumption of spherical plasma plume, instead of elliptical nature of the plasma plume.

Further as in the case of single plasma plume, in colliding plasma also the expansion of the plasma plume in axial direction slows down in presence of field. Visual examination of the Fig. 2(b) shows that optical emission from the plasma plume increases in the presence of field up to 400 ns delay time as compared to the field free case. This can be attributed to increased ionic emission as will be discussed in the next section. This is also confirmed by the spectral emission and electron temperature estimation as will be discussed latter. These images clearly demonstrate that dynamics and shape of the colliding plumes, overall luminosity and formation of interaction zone is highly dependent on the presence of external magnetic field.

B. Optical Emission Spectroscopy (OES)

Optical emission spectroscopy is used to investigate plasma electron temperature, density and variation in intensities of lines from various charge states. Figure 3 shows temporal changes in the intensity of characteristic Al I 396.15, Al II 466.3 and Al III 414.99 nm lines with $B = 0$ and 1000 Gauss. Al I line shows increase in intensity at longer times for field free case. Interestingly its intensity is considerably diminished in the presence of the field and almost unobservable at longer times which is in sharp contrast to the field free case. On the other hand, for ionic lines enhancement in intensity is observed. In contrast to the monotonic decrease in intensity in field free case, intensity of Al$^+$ increases up to certain value at 300 ns delay time, as seen for Al II 466.3 nm, and then starts decreasing with further time delays. The enhancement in the intensity of Al$^+$ ions is probably because of the increased temperature due to Joule heating in external field. This is also supported by increase in the ionization rate coefficients with introduction of magnetic field, which will be discussed latter. In the foregoing discussion, it is shown that the electron density is also increased after the introduction of magnetic field, which is in line with our observation regarding increased ionization.

As mentioned earlier, it is interesting to note that the intensity of Al$^{2+}$ line (414.9 nm line) increases at longer delay times whereas the intensity of neutral Al I (396.1 nm) line decreases. To substantiate this we have estimated magnetic diffusion time described by $t_d = \frac{4\pi \sigma R_b^2}{c^2}$, where $\sigma$ is plasma conductivity which can be estimated from Spitzer formula. The estimated magnetic diffusion time for $R_b = 1.77$ cm and 2 eV temperature is 537 ns for $Z = 2$. This qualitatively explains the increased Al$^{2+}$ emission at longer times. This can be attributed to the increase in plasma electron temperature and subsequent density because of Joule heating in the presence of magnetic field. Here, we would again like to mention that in field free case neutral emission increases at longer times which has been attributed to increased three body recombination.

Electron temperature has been estimated by using Boltzmann relation, $I_{ij}/I_{kl} = [(\nu_{ij} A_{ij} g_i)/(\nu_{kl} A_{kl} g_k)] \exp[-(E_i - E_k)/(k_B T_e)]$ from Al (II) 466.3 and 559.3 nm lines. In this relation, $I$ is the line intensity of the transition between two energy levels, $\nu$ is the frequency of the line, $A$ is Einstein’s...
Ionization rate coefficients for both $\text{Al}^{+}$ and $\text{Al}^{2+}$ lines with and without external field has been estimated from the eqn. 1. Temporal evolutions of electron temperature and density of colliding plasma with and without B are shown in Fig. 4. It can be seen that electron temperature increases initially up to 200 ns time delay. After that it decreases with further delay time in field free case. The temporal profile of electron temperature in presence of magnetic field can be divided in three steps. After increasing at initial time, it decreases rapidly and is nearly unchanged within the range of 300 to 500 ns delay time. Again, it decreases from 500 to 600 ns. However, throughout this temporal evolution, the electron temperature is always higher in presence of magnetic field B as compared to field free case. Electron density is increased in the presence of magnetic but appears to show similar type of trend with time as in case of electron temperature.

Beside ionic line intensity, electron temperature and density, we have also calculated the ratio of $\text{Al}^{2+}$ and $\text{Al}^{+}$ and ionization rate coefficients for $\text{Al}^{+}$ and $\text{Al}^{2+}$. Ratio of $\text{Al}^{2+}$ and $\text{Al}^{+}$ ions has been calculated by using Saha relation described by $\frac{n_i}{n_n} \approx 2.4 \times 10^{21} \frac{T^{3/2}}{n_i} e^{-U_i/k_BT}$ and is shown in Fig. 5 for both the cases i.e. with and without field. Here, $n_i$, $n_n$, $T$, $U_i$, $k_B$ represents ion density, neutral density, plasma temperature in Kelvin, ionization potential of atoms and Boltzmann constant, respectively. Figure 5 shows substantial increase in $\text{Al}^{2+}$ ions. Ionization rate coefficients discussed in the next section also qualitatively support it.

Ionization rate coefficients for both $\text{Al}^{+}$ and $\text{Al}^{2+}$ lines with and without external field has been estimated from the eqn. 1.

$$\kappa_{pi} = \frac{9.56 \times 10^{-6}(kT_e)^{-1.5} \exp(-\epsilon_{pi})}{e_{pi}^{233} + 4.38 \epsilon_{pi} + 1.32 \epsilon_{pi}^2} \text{ cm}^3 \text{ s}^{-1} \quad (1)$$

Here, $\epsilon_{pi} = E_{pi}/kT_e$ and $T_e$, $E_{pi}$, p, i represents electron temperature, ionization potential, principal quantum numbers of initial and ground state, respectively. Figure 6 shows the temporal evolution of ionization rate coefficient of colliding plasma at $B = 0$ and 1000 Gauss in vacuum. This figure shows an initial increase in ionization rate coefficient for both $\text{Al}^{+}$ and $\text{Al}^{2+}$ lines and then decreases with time. Further, it shows decrease from 200 to 300 ns delay time. After that, it decreases at slower rate with further delay time. However, the increase in this rate is clearly visible with the introduction of magnetic field which describe fairly the spectral behaviour of observed neutral and ionic lines (Fig. 3) i.e. increased emission of $\text{Al}^{+}$ and at later times enhanced intensity of $\text{Al}^{2+}$ line as mentioned earlier.

Briefly two main striking observations are noticed in the interaction zone with the introduction of magnetic field. First, no sharp interaction zone is observed which is expected from the estimation of collisionality parameter, instead a blurred overlapped region is observed. This can be understood because of the gyration of ions in the presence of magnetic field. Second observation is increased emission from higher ionic states at longer times in contrast to increased neutral emission in field free case. This fact can be anticipated due to Joule heating effect in the presence of magnetic field.

**IV. CONCLUSION**

It can be mentioned that the present study is an initiative in laser produced colliding plasma interaction in presence of an external magnetic field. Briefly, contrary to field free case no sharp interaction region is noticed in the presence of magnetic field. Further, an increase of $\text{Al}^{2+}$ emission has been observed in the presence of the magnetic field which is in sharp contrast to field free case where neutral emission dominates at longer times. This has been attributed to Joule heating and subsequent increase in ionization. We believe the present work will be interesting from the viewpoint of manipulating colliding plasma properties with the introduction of magnetic field.
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