Chapter 5

Image Analysis of Lithium Plasma Plume in Variable Transverse Magnetic Field

Abstract

Effect of transverse magnetic field on the geometry and features of the lithium plasma plume generated from solid and thin film target has been studied using fast imaging and emission spectroscopy. Enhancement in the overall emission intensity as well as appearance of distinct structures in the plasma plume in the presence of magnetic field has been observed. By introducing a variable magnetic field, the influence of various atomic processes in expanding plasma plume across the transverse magnetic field has been studied.
5.1. Introduction

The interaction that occurs between an externally applied magnetic field and plasma is an important topic with potential applications ranging from astrophysics to pulsed power and fusion. In recent years, the effect of magnetic field on the expansion of laser-produced plasma plume has been the subject of intensive research because of its relevance in various applications like thin film deposition, debris mitigation, development of extreme ultra-violet (XUV) lithographic sources, analytic detection limit enhancement in laser-induced breakdown spectroscopy (LIBS) etc{1-8}. Earlier studies revealed that expansion of plasma in the presence of magnetic field may initiate several interesting physical phenomena in the overall plume dynamics such as conversion of the plasma thermal energy into kinetic energy, plume confinement, ion acceleration, emission enhancement, plasma instabilities etc. Among this, there is a particular interest to investigate the influence of magnetic field for the plasma confinement {9-11}. In pulsed laser deposition (PLD), plasma confinement in a converging magnetic field leads to more excited plasma and a reduction in the deposition temperature {17, 18}. It has also been observed that magnetic field can control the external plasma parameters in a variety of ways {9, 11, 13, 21}

In this chapter, we discuss the influence of external magnetic field on the propagation dynamics of laser plasma formed from Li solid as well as LiF-C thin film target. Uniform magnetic field applied in the transverse direction to the expanding plasma and the field strength was varied from zero to 4000 Gauss. Imaging of the expanding plasma was carried out using ICCD. Li spectral line emission analysis also performed in order to confirm the results obtained from the imaging data. Analysis of the experimental data revealed several interesting observations at different time periods. The overall plume shape and intensity variations are major characteristics, which have been studied.
5.2. Review of earlier works

Considerable work has already been carried out both theoretically and experimentally to understand the influence of external magnetic field on laser produced plasma. Bhadra et al. (19) theoretically studied the expansion of plasma in the presence of magnetic field and has postulated that, cloud of plasma will be stopped by the magnetic field $B$ at a distance $R \sim B^{-2/3}$. The periodic pulsations of the plasma boundary against the magnetic field when $\beta > 1$ observed by Tuckfield et al. (20) were in approximate agreement with the theory proposed by Bhadra with inclusion of a condition that the energy losses due to radiation and particle losses along and possibly across the field lines been taken into account.

Peyser et al. (21) demonstrated that, plasma expansions strongly collimated in the direction transverse to both the initial flow and the magnetic field, but jet-like in the direction parallel to the initial flow. Structural changes in the plasma geometry and instabilities generated as result of the magnetic field were studied using fast framing cameras. Further, they attributed that $E \times B$ is responsible for the jet like structures, whereas instabilities caused the edge structures. Plume emission enhancement when the plasma expands in a magnetic field was another interesting observation reported in many cases (10-13). Enhancement in emission was found to be dependent on the intensity of external magnetic field and correlated with an increase in confinement of laser produced plasma as well as generation of instabilities in the plasma. Mostovych et al. (26) investigated the expansion of laser-produced barium plasma in 0.5- 1 T transverse magnetic fields, and reported the focusing of plasma jet in the plane perpendicular to the field, while in the plane of the field the plasma expands along the field lines and this appears as flute-like striations. The narrowing of the plasma jet was understood in terms of the configuration of the plasma polarization fields, while the flute structure was identified as electron-ion hybrid velocity shear instability. Dimote and Wiley (27) measured the magnetic profile and plasma structure for nearly spherical exploding plasmas in a magnetic field. The diamagnetic cavity and plasma radii scale with the...
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magnetic containment radius over a wide range of ion magnetization. Plasma instabilities were also observed which evolve from short to long wavelengths and affect the evolution of the magnetic field.

Bryunetkin et al. {28} reported the first experimental demonstration of the difference in the emission of spectral lines by ions of different degrees of ionization in a laser-plasma expanding in vacuum in the presence of a transverse external magnetic field strength of 0.3 T. Enhancement in line emissions were observed and they concluded this result as the action of plasma focusing due to the magnetic field. A qualitative explanation of the observed emission pattern has also been provided with numerical modeling.

Confinement of the laser-produced plasma by a curved magnetic field was investigated by Tsui et. al. {29, 30}. In this study, an axial magnetic field with a maximum strength of 2.2 kG was used to confine and guide a laser produced carbon plasma. The measurement has been conducted using an array of Faraday cups positioned at the exit of the guide field and found that approximately 20% of the original plasma was confined by the magnetic field.

Plume splitting was another interesting observation noticed in the presence of magnetic field. Combined diagnostics using emission spectroscopy and fast imaging by Neogi and Thereja {31} reported the splitting of plume into two assymmetric lobes in the presence of an inhomogeneous magnetic field. Each of these lobes has three components viz. the fast, intermediate, and slow. The plume spitting has been explained on the basis of J x B force acting on the plume. Moreover, oscillations were also observed in the temporal profile of the plume, in the presence of magnetic field. These oscillations were observed at a location where species are at the outermost front, and this is attributed to edge instability in magnetic field. Harilal et al. {32, 33} suggested the role of backflow of particles towards the target for the appearance of lobes. Qindeel et al. {34} studied the plume behaviour with imaging CCD for varying magnetic field for Al, Cu and brass targets. They
suggested that plume structure might result from the Lorentz force exerted by the field. Jet-like structures in the plume in the presence of magnetic field has been attributed to instabilities by Rafique et al. \{35\}. Despite these reports, a comprehensive temporal imaging study with varying field is necessary to understand the field effect. Studies carried out in this direction are described in this chapter.

5.3. Experimental details

The investigations were carried out by means of the experimental setup described in chapter 2. Only the main features and additional parts are briefly summarized here. The experiment was carried out in a cylindrical stainless steel chamber, evacuated to a base pressure < 2x10^{-5} Torr. For LPP studies, ½ inch diameter solid Li rod with purity 99.999% and for LBO studies LiFC thin film target was used. Fundamental emission (1064 nm) from an Nd:YAG laser was used to ablate the target. The spot size of the laser beam was set to about 1 mm diameter at the target to achieve average power density of ~ 10^9 W/cm^2. A pulsed power system consisting of capacitor bank and a wire wound solenoid was used to produce a magnetic field in the range, 0 – 3000 G with a flat-top duration of of 40 \mu s which was much larger than the plume duration \{36\}.

Both OES and imaging diagnostics were performed simultaneously on the two sides of the chamber. Each of these techniques has its on merits and demerits for plasma diagnostics. Due to certain limitations, some results cannot be correlated with each other. For instance, enhancement of emission that comes out from distinct lines was easier to understand by analysing OES data. On the other hand, plume geometry alterations induced due to magnetic field were more visible in ICCD images than in OES data. To investigate the effects of the magnetic field on the plasma plume, the emission spectrum for two characteristic emissions from lithium neutral and from lithium ion has been recorded by varying the field.
An ICCD camera (4 Picos, Stanford Computer Optics, Inc.) having variable gain and gating on time, has been used to record the time resolved images of the plume luminescence in the spectral range of 350 - 750 nm. In the present experiment, gate opening i.e., image integration time was set at 4 ns. Temporal evolution of the LPP plume has been obtained by varying the time delay from 100 to 4000 ns between the laser pulse and the opening time of ICCD gate. Five images were recorded under similar experimental conditions. These images were found to be nearly identical in shape and the reproducibility of the emission intensity was better than 5 %. To find the emission profile along the direction of plume expansion, plume images were binned along the vertical column of images.

5.4. LPP of Li in magnetic field

The plasma expansion from solid Li target across the transverse magnetic field was recorded by ICCD camera at different magnetic field strengths, varying from 0 to 2800 G and is shown in the Fig 5.1.

![Figure 5.1 Images of plume recorded at two different time delays 300 ns and 700 ns as a function of the field strength.](image)

These images were recorded in vacuum with a time delay of 300 ns and 700 ns with respect to the laser pulse. Images at these particular delays are showing interesting features on the plume intensity distribution. Each of these images represents spectrally integrated emission intensity in the region 350 – 750 nm emitted from different plume species for a fixed value of magnetic field.
From Fig.5.1, it is clearly visible that, the plume was modified drastically by the influence of uniform magnetic field. The changes induced under the influence of field include the enhancement in intensity and modification in the plume geometry. These two aspects are explained separately in the coming sections of this chapter. Emission spectroscopy was also conducted in every case to have better understanding of the dynamics under magnetic field.

5.4.1. Plume emission under magnetic field

In the absence of the magnetic field, ablation of lithium into vacuum produces an intense luminous plume that expands normal to the target surface. The expansion is primarily governed by the initial density/ pressure gradient inside the plume and is well explained theoretically in terms of adiabatic and self-similar expansion model {18}. Comparison of the images recorded at different field strengths shows that, the shape and the intensity of the plasma plume are completely modified on introducing the transverse magnetic field.

![Figure 5.2](image)

*Figure 5.2 Variation of the total integrated intensities of plume images recorded at three specific time delays after the laser hit.*
Figure 5.1 shows plume geometry and emission as a function of field strength at three different time intervals. For field strength 0 to 800 G, plume size has increased and with further increase in field i.e., > 800 G plume becomes confined. Many authors have already reported the enhancement of emission in the presence of magnetic field. To get degree of enhancement quantitatively, we have integrated the intensity of the plume images recorded using ICCD and are shown in Fig. 5.2

The above figure (Fig 5.2) gives an understanding of the plume intensity variations as a function of field strength at three specific time delays. Initially for field strength of 400 to 800 G, the plume undergoes significant enhancement in intensity and with further increase in field strength, the enhancement goes down. This information can be correlated to the ICCD image data shown in Fig. 5.1. On increasing the field strength beyond some range (> 800 G), the plume size becomes smaller as a result of plume confinement and intensity increases over a small area. Since the dynamic range of ICCD camera limits the maximum intensity that can be recorded, and this makes the integrated plume intensity data exhibiting a different trend with increase in field.

In order to confirm the plume enhancement, we have recorded the Li neutral emission lines. Figure 5.3 show the temporal evolution of Li (I) 670.8 nm \(2s^2\,^2S_{1/2}\rightarrow 2p\,^2P_{3/2,1/2}\) line at different magnetic fields. It can be seen that enhancement in the emission takes place when the field is increased. Moreover, the profile is broadened with some small structures. However, unlike 670.8 nm, for 610.3 nm \(2p\,^2P_{1/2,3/2}\rightarrow 3d\,^2D_{3/2,5/2}\) line shows a decrease in emission although the profile shows some broadening (Fig. 5.3).

To explain enhancement in line emission, various mechanisms like increase in ionization, confinement, increase/ decrease in effective plasma density, increased radiative recombination and increase in both confinement and radiative recombination have been proposed. As most of the earlier experiments were
performed at constant magnetic field, no definite mechanism for enhancement could be identified.

Figure 5.3 Intensity variations with magnetic field of (a)670.8 nm line and (b)610.3 nm line

A recent study explained the role of atomic process during the plume dynamics under the influence of magnetic field \{44, 45\}. For this, the photoemissivity coefficients (PEC), has been calculated from Atomic Data Analysis Structure (ADAS) database \{46\}. This research addressed the difference in enhancement on the basis of change in PEC’s. For 670.8 nm, coefficients for electron impact excitation(PEC\textsubscript{ex}) is significantly higher than coefficients for recombination(PEC\textsubscript{re}) indicating that electron impact dominates over recombination and hence will result in the enhancement in intensity with the increase in field because of increase in electron temperature although a small increase in electron
density is also expected because of confinement. However, the overall effect of Joule heating appears to be dominating. On the other hand, for 610.3 nm lines, there is less difference in $\text{PEC}_{\text{rec}}$ and $\text{PEC}_{\text{ex}}$. As the LPP plume is expected to have ionic species, it appears that net contribution from recombination dominates in this case. This explains the decrease in intensity with increase in field as $\text{PEC}_{\text{rec}}$ decreases with increase in temperature.

In addition to the enhancement of the plume emission, various instabilities like structures and splitting are also induced in the plume under the influence of magnetic field and these results are presented below.

### 5.4.2. Plume geometry under magnetic field

Plume modifications are most pronounced in the range of field from 400 G to 1600 G. The degree of modification of the plume was not so visible after a field of $B > 1600$ G.

In order to get a better presentation of axial variation of emission intensity in the presence of magnetic field, the cross-section of the plume emission intensity along the expansion axis is binned and included in Fig.5.4. Binned intensity profile plot of the plume images gave precise information about the plume splitting and spatial location at which the intensity peak appears. Initially in the presence of magnetic field above 400 G, the plume splits into two lobes ($P_1$ and $P_2$) in the direction of expansion. Figure 5.4 also shows the formation of another structure $P_3$ with increase in the magnetic field ($> 400$ G) and this well-defined third lobe ($P_3$) is clearly visible at a field of 1200 G field. However, $P_3$ diminishes with further increase in the field and almost disappears when the field is $B > 1600$ G and finally attains a two lobe structure. Here we rule out the possibility of $P_2$ and $P_3$ being merged. Had the merger caused it, a large enhancement in the emission intensity should have taken place for higher field values, which, of course, is not observed in the present case. Another noticeable observation is that the increase in magnetic
field largely affects the leading portion of the plasma plume as compared to the initial portion closer to the target.

Figure 5.4 Sequence of images at 300 ns along with the corresponding intensity profiles for different magnetic fields
Plume splitting in the presence of magnetic field has been observed previously by several authors \cite{32, 33, 37} and they explained this phenomenon on the basis of fluid MHD model. According to this model, plasma plume can be treated as a conductive medium, which expands in external magnetic field and an internal diamagnetic current arises to exclude the field from the interior. This diamagnetic current interacts with the magnetic field through $\mathbf{J} \times \mathbf{B}$ force that accelerates or decelerates different regions of the plasma plume, depending on the direction of the diamagnetic current within the plume causing the plume splitting along the expansion direction.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5_5.png}
\caption{Overlapped intensity profiles for various magnetic fields for 300 ns delay.}
\end{figure}

It can be noted that the above conclusions drawn in most of the previous reports were based on experimental results with fixed magnetic field. Hence,
experiments with variable magnetic field are essential to explore the role of $J \times B$ force in expanding plasma plume across the transverse magnetic field. We, therefore, attempted to look more closely at the plume splitting in the magnetic field by investigating the splitting pattern for variable field strength. In this regard binned emission intensity profiles along the expansion axis corresponding to different magnetic fields are overlapped as shown in Fig.5.5.

Interestingly, the peak positions of P1 and P2 are independent of the field strength and appear at the same axial position for the entire field range. However, front portion of the plume slowly converges with increasing the magnetic field. This is an important observation because variation in the separation between two components is expected with increase in the field, if $J \times B$ force is responsible for the splitting. This indicates that instead of $J \times B$ force, some other processes should be responsible to produce the above phenomenon.

Another suggestion for the presence of lobes observed in the imaging study was given by Harilal et al. \cite{33} where the studies were carried out at a fixed magnetic field. They estimated the bubble time and found that splitting takes place at longer times than the bubble time and subsequently attributed it to the backflow of particles. We have also calculated bubble radius and hence calculated bubble time from it. A typical bubble radius

$$R_b = \left(\frac{3\mu_0E_l}{2\pi B^2}\right)^{1/4}$$  \hspace{1cm} (5.1)

where $E_l$ is laser energy and $B$ is magnetic field strength. For the experimental parameters $E_l = 200$ mJ and at 400 G field the calculated value of bubble radius is $\sim 4.2$ cm and corresponding bubble time $(2R_b/v)$ which comes to about $\sim 760$ ns for an expansion velocity of $\sim 1.1 \times 10^7$ cms$^{-1}$. Since the lobes appear even at the lowest field (400 G) and at 300 ns time delay, it is difficult to correlate
the presence of lobes to the collapse of the bubble and subsequent backflow of particles, as the bubble lifetime is comparatively longer.

Another aspect that can result in instabilities in the plume is the self-generated magnetic field. The self-generated field can be estimated by (38-40)

\[ B \left( \frac{kT}{e zv} \right) e \leq / (2) \]

where \( k \) is Boltzmann constant, \( T_e \) is the plasma temperature, \( e \) is electronic charge, \( z \) is the distance at which field is to be calculated and \( v \) is the expansion velocity of the plume. For \( z = 6 \) mm distance, the maximum value of \( B \) is \( \sim 80 \) G, which is much less as compared to the external applied field values. Hence any instability due to the interaction of self generated magnetic field and applied magnetic field can be simply ruled out.

We feel that the magnetic field significantly influences the plasma parameters and hence the associated atomic processes in different regions to different extents in the plume as the composition changes along the expansion direction, causing the structure formation in magnetic field. The presence of magnetic field increases the electron temperature due to Joule heating (11) and electron density due to magnetic confinement (10, 11, 29). Moreover, the plume expansion in the transverse magnetic field may result in the cyclotron motion of electrons and ions. This will significantly increase the probability of electron-atom/ion collisions, which in turn lead to enhancement in the emission intensity of the expanding plume. Therefore, the overall enhancement in emission intensity can be considered as the net contributions from electron impact excitation as well as recombination processes.

It is known from earlier studies that LPP plume front is mainly composed of energetic ionic species and therefore ionic emission is supposed to form the plume front in the observed images. On the other hand, the slow moving species dominated by neutrals represent the trailing portion of the plume. The above argument is strongly supported by optical emission spectroscopic data (45) where
strong Li II emission line appeared at shorter time delays as compared to that of Li I emission. Further, it is evident that the typical electron temperature and electron density of Li plasma are around 2 eV and $10^{17}$ cm$^{-3}$ under similar experimental conditions \cite{45}.

Conclusions are made on the basis of the above discussion that enhancement in the emission intensity; especially at the plume front and the appearance of elongated leading portion of the plume (P3) in the presence of the magnetic field is mainly due to the increase in excited ionic species by recombination processes. It is likely that with the introduction of the field, confinement may take place, which will result in increased electron density and hence increase the electron-ion recombination.

Careful examination of Fig.5.1 reveals that the magnetic field largely influences the front portion of the plume as compared to that of the trailing part. Plume front gradually converges into small volume with increase in the field. This could be understood as follows. The leading portion of the plume is mainly composed of energetic ions. It appears that ejected ions experience the resistive force in the presence of magnetic field and are gradually confined in small volume with increasing the magnetic field. For the present experimental conditions, the estimated bubble radii for the magnetic fields of 400 G and 2800 G are 4.2 and 1.15 cm respectively. The average deceleration ($g = v^2/2R$) in the presence of 2800 G magnetic field is $5.3 \times 10^{13}$ cm/s$^2$. Here the initial velocity of the plume ($v = 1.1 \times 10^7$ cm/sec) is obtained by the plume image at 300 ns in the absence of magnetic field. The deceleration is also calculated by considering the plume images in the absence and presence of magnetic field using time of flight method. The agreement between the experimentally observed deceleration ($\sim 4.0 \times 10^{13}$ cm/s$^2$) and calculated one suggests the confinement of ion rich plume front in the presence of magnetic field.
Figure 5.6 Sequence of images at 700 ns along with the corresponding intensity profiles for different magnetic fields
Similar analyses were performed for the images taken at 700 ns delay and is shown in Fig. 5.6. The shape of the plume is entirely different from those observed at 300 ns. It can be noted that the emission intensity of the emitting species thermalizes rapidly with increasing time delay. It appears that emission from the ionic species i.e., front portion of the plume represented by P2 & P3 is decreased significantly or disappears and only neutral-rich trailing portion of the plume appears at this time delay. The confinement of neutral species can be understood in the following manner.

Figure 5.7 Intensity profiles of images showing intensity enhancement. All these images were recorded at an argon pressure of $10^{-2}$ Torr at various time delays after the plasma formation.
At 700 ns, plume emission comes from both slow moving neutrals as well as neutral produced by the recombination of ionic species. As we have already discussed the ionic species experience the resistive force in the presence of magnetic field, which is reflected in the reduction of emission length from neutrals. Further, the images at 700 ns clearly show that the emission intensity at the edge of the plume (near the pole) is high in the presence of the magnetic field. This is because electron current density at the outer most boundary of the plume is expected to be high in the presence of the magnetic field.

Experiments were also conducted to understand the effect of magnetic field when the plasma is generated in an ambient gas environment. For this, we introduced argon gas into the chamber. As we had discussed in the earlier chapters, the presence of ambient gas enhances the intensity and lifetime of the plume. Figure 5.7 shows the images of plasma created from solid lithium target kept in ambient gas in the absence and presence of a uniform field of 2000 G.

5.5. LBO of LiFC in magnetic field

In the previous section of this chapter, we have been discussing the influence of external magnetic field on the dynamics of laser-produced plasma from Li solid targets. From the analysis, we found many interesting changes in the presence of field and alteration in the geometrical shape with varying magnitude of field.

This section of the chapter discusses the study conducted to investigate the effect magnetic field on the propagation dynamics of plasma generated from LiFC thin film target. Super-thermal neutral atomic beams lithium and carbon, produced by laser-blow-off (LBO) technique are extensively used to measure the edge parameters of high temperature Tokamak plasma. The presence of Tokamak’s magnetic field is expected to considerably affect the neutral and atomic ion beams. This motivated us to conduct experimental study to investigate the effect of magnetic field on the lithium plasma produced from LiFC target by LBO scheme.
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The experimental setup used is same as the one described in the earlier part (Sec 5.3) of this chapter. The target used is a thin film LiFe coated over a quartz substrate. Optical emission spectroscopy and/or imaging techniques were used as diagnostics for studying the dynamics of these plasma plumes.

During the initial phase of the studies, we have recorded the plume images at various time delays as well as at different field strengths.

![ICCD images of the plume recorded in vacuum for different magnetic fields. Above images are recorded at 400 ns and 600 ns. Colorbar shows the normalized intensity in arbitrary unit.](image)

In order to study the influence of varying magnetic field, the magnitude of field was varied from 0 G to 2000 G and the images were recorded using ICCD (Fig.5.8). In general, enhancement of the plume intensity is observed at different
magnetic field strengths. Plume shape changes are not as prominent as that observed in the case of LPP plasma from Li solid target. Similar to the observations in solid Li target, changes induced for the LBO plume is maximum for the field strength in the range 400 G to 1600 G.

It has already been discussed that plume undergoes significant changes when it expands in an ambient medium. In the present investigation, we have studied the combined effect of magnetic field and ambient gas over the expanding LBO plasma. Figure 5.9 shows the images recorded at different pressure levels of argon gas and the field was varied from 0 to 2000 G.

Figure 5.9 ICCD images of the plume recorded at an argon pressure of $10^{-2}$ Torr and 1 Torr for different magnetic fields. Above images are recorded at 600 ns and 1000 ns. Colorbar shows the normalized intensity in arbitrary unit.
Since it is difficult to get a quantitative measure of the overall plume enhancement from the images, the plume images are integrated and are shown in Fig. 5.10. It is clear from the Fig. 5.10 that plume intensity enhanced with increase in magnetic field. This effect was almost similar in both pressure levels $10^{-2}$ Torr and 1 Torr. Considering the plume structure changes at different magnetic field strengths, the changes induced is almost negligible as compared to the plume modifications observed in the case of plasma plume from Li solid target.

Imaging studies produce resultant signals derived from the overall emission of the plasma. Due to these limitations, ICCD imaging alone would not make it possible to understand the exact details on the changes that plasma expands in a magnetic field. From the earlier studies, it is clear that the magnetic field affects in a different way on various emission lines. So the results obtained using the fast imaging technique has confirmed and expanded by relating the same with corresponding emission spectroscopy data which are recorded for the same ablation.
For spectroscopic studies, we have chosen two spectral lines of neutral lithium Li (670.8 nm) and Li (610.3 nm). Figure 5.11 shows the variation in the neutral emissions 670.8 nm and 610.3 nm for different magnetic fields in the range 0 –2000 G observed at a distance z = 6 mm from the target.

![Figure 5.11](image)

**Figure 5.11.** Temporal profiles of 670.8 nm line (a) and 610.3 nm (b) for various magnetic fields at z = 6 mm.

There is a significant difference in the shapes of temporal profiles of neutrals obtained with and without magnetic field. In vacuum, with increase in the magnetic field, the profile shows structure formations as well as intensity enhancement. The enhancement in intensity for 670.8 nm line is significantly higher as compared to the neutral line 610.3 nm. Enhancement of 7.3 times for 670.8 nm in overall intensity was observed in the presence of magnetic field.
Figure 5.12 Variation of the total integrated intensities of 670.8 nm and 610.3 nm spectral lines with magnetic field at z = 6 mm.

The effect of magnetic field when the plasma formed in an ambient environment is entirely different as compared to that in vacuum. When the ambient pressure increased to $3 \times 10^{-2}$ Torr of argon, the temporal profile of 670.8 nm line exhibits an interesting change with increase in the field. Its leading part shrinks sharply and the overall profile becomes narrower although there is an increase in the overall intensity as compared to the field free case. However, 610.3 nm emission line shows a different trend. The overall emission enhancement in the intensity particularly at the trailing part as the field is increased, which is prominently different to what is observed in the case of 670.8 nm line. Furthermore, unlike in the case of vacuum, the structures in the temporal profile are not evident at this pressure (Fig.5.13). With further increase in pressure to 1 Torr, there is not much pronounced effect of the magnetic field on both 670.8 nm and 610.3 nm temporal profiles unlike in the case of $3 \times 10^{-2}$ Torr.
Figure 5.13 Temporal profiles of 670.8 nm (left panel) and 610.3 nm (right panel) in $10^{-2}$ Torr and 1 Torr for different magnetic fields. The profiles were recorded at $z=6$ mm.

A similar observation, i.e., the difference in temporal profiles for the two neutral lines (670.8 nm and 610.3 nm) under the influence of magnetic field has been discussed in the earlier part of this chapter. The change has been qualitatively understood in terms of computed photon emissivity coefficients (PEC) using atomic data and analysis structure (ADAS) \{46\} for both the lines.

The observed behavior in the intensity of these two transitions in the presence of the magnetic field and at different ambient pressures can be explained by considering the following processes (i) Joule heating due to the presence of the magnetic field and hence an increase in electron temperature \{11\}, (ii) increase in
electron confinement in the presence of the magnetic field \cite{42, 43}, (iii) heating due to the ambient gas itself \cite{49} and (iv) increase in electron density as a result of interaction between plume plasma and ambient gas.

Earlier studies reported \cite{44, 45} the enhancement in the intensity of these lines in the presence of magnetic field in vacuum. This was attributed to an increase in electron impact excitation, which increases with increase in electron temperature as well as electron density. The difference in the intensity enhancement for these two lines has been attributed to the difference in electron impact excitation for these transitions due to increase in Joule heating (increased electron temperature) \cite{11}. Moreover, the temporal evolution of the plume in vacuum and in the presence of the field is correlated to the magnetic diffusion time i.e., time essential for Joule heating, which is $\sim$4 to 1 $\mu$s for our experimental parameters. This means that with increase in the field, the plume will be affected at shorter time delays.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5_14.png}
\caption{Temporal profiles of Li I 670.8 nm (a) without field, (b) 2000 G; Li I 610.3 nm (c) without field and (d) 2000 G for various distances.}
\end{figure}
In the presence of the ambient gas, it should be noted that collisions start between the plume species and ambient atoms, when the plume dimensions are of the order of the mean free path of the ejected species \{49, 50\}. We have already discussed the influence of ambient gas on an LBO plume in chapter 3. Using the Westwood model \{47\}, the estimated mean free path for lithium atoms is \(\sim 4.8 \text{ mm at } 3 \times 10^{-2} \text{ Torr}\). This value of mean free path reconfirm the fact that the plume expands into collisional regime at this pressure for \(z = 6 \text{ mm}\). In this regime, interpenetration of the plasma plume into the ambient gas occurs, which causes an increase in the collisions between the plume species and the ambient gas atoms. Hence, there will be an increase in the electron density in this pressure regime. It is also observed that at this pressure, plume front temperature is increased (\(\sim 7 \text{ eV}\)) \{52\}. However, as the time evolves, plasma electrons quickly lose their kinetic energy through elastic and inelastic collisions with the ambient gas atoms. As a result, plasma with high density and low temperature especially at the trailing portion of the plume is presumably formed.

At sufficiently higher pressures (1 Torr), the plume material pushes away the background gas. The compressed gas restricts the diffusion of the plume material and an interface is formed. On the development of the interface boundary between the plume and the surrounding gas, the expansion transforms from collisional regime to hydrodynamical regime \{Chapter 3\}. The compressed gas restricts the expansion of the plume, thereby confining the plume in a smaller volume \{48, 49\}. Combined effect of the magnetic field and the ambient gas on the temporal evolution of neutral emission lines can be understood as follows. Apart from the heating of the plume front and increase in electron density in the presence of the ambient gas, the presence of magnetic field also increases the electron temperature due to Joule heating and electron density due to magnetic confinement \{11\}. In vacuum, the appearance of broad component with field can be attributed to the presence of slow neutrals emanating from the direct vaporization of lithium.
This explains the appearance of a broad shoulder as well as greater intensity enhancement for the 670.8 nm line with increasing magnetic field.

At \( z = 6 \) mm, plume-atom collision causes an increase in the electron temperature as well as density and hence increase in the electron impact excitation dominates for 670.8 nm which is strongly dependent on the temperature and density. Further at 1 Torr pressure, plume already gets confined and hence it is expected that magnetic field may not bring about any more prominent changes in the line emission.

It was found that there is a drastic reduction in the intensity of P4 as a function of magnetic field. This can be attributed to the role of electron drift induced by the penetrating magnetic field lines. As the temperature in this region is very low, the magnetic field lines can easily penetrate and cause the electrons to drift away from the region of observation causing reduction in the number density of electrons. As the observed intensity is directly proportional to the electron density, a significant reduction in intensity as a function of magnetic field is not unexpected.

**Figure 5.15** Temporal profiles of 548.4 nm line for various magnetic fields at \( z = 2 \) mm.
Scenario is different for the ionic spectral line. Interestingly, the temporal behavior of Li II 548.4 nm ionic line did not show any significant changes in the presence of the ambient gas and magnetic field as shown in Fig. 5.15. The dominant mechanism for the excitation of 548.4 nm ionic line has been found to be the recombination mechanism \cite{51}. In vacuum and for low fields, the electron density is not affected much and hence the intensity is not expected to get changed significantly. However, for higher fields due to increase in confinement a small increase in density is expected, which, of course, will result in increased intensity. For 3x10^{-2} Torr pressure, as the confinement may take place even for lower fields, we can expect an increase in intensity due to increased electron density. For higher fields, electron temperature also increases resulting in decreased recombination and hence decreased intensity.

In this section, we have discussed the effect of magnetic field on the plasma plume formed from LiFC target. The emission was monitored by fast imaging using ICCD and two distinct neutral emission lines from lithium have been observed. In the presence of magnetic field, the temporal profiles of these lines showed distinct features with an enhancement in their intensity.

5.6. Conclusions

In this chapter, we have discussed the results of the experiments conducted to understand the effect of magnetic field on the dynamics of plasma created from Li solid as well as LiFC thin film target. Plume images at various experimental conditions were recorded using ICCD. Optical emission spectroscopy also employed in all cases to get better insight into the plume evolution in the presence of magnetic field. Enhancement of the overall emission of the plume as well as structural modifications was observed as a function of field strength.

First section of the chapter demonstrates the plume formed from a solid lithium target under the influence of magnetic field. Fast imaging of the laser produced plasma plumes showed the appearance of structures in presence of
transverse magnetic field. The observed findings indicated that instead of $J \times B$ force, atomic processes get affected by magnetic field in different regions to different extents causing the structure formation. Evidence of instability or collapse of the bubble has not been found to be the cause of the structures.

Influence of field on plasma formed from LiF-C thin film target was the subject of matter in the second part of this chapter. Plume imaging and spectroscopy was performed for plume formed in vacuum and in argon ambient gas. Analysis of imaging data showed the enhancement of the plume in the presence of magnetic field while OES data illustrate the presence of various structures. The temporal profiles for the two neutral lines (670.8 nm, 610.3 nm) showed distinct features at the trailing part at $3 \times 10^2$ Torr argon pressure. At further higher pressures (1 Torr) the effect of field was not that prominent. Lithium ionic lines (548.4 nm) were not influenced much by the magnetic field. The difference was explained by considering electron impact excitation and recombination processes and ambient gas diffusion in collisional and hydrodynamical regimes.
5.7. References


Plasma expansion in a magnetic field


46. Atomic Data Analysis Structure (ADAS).online at http://adas.ac.uk


